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MATERIALS
OF CONSTRUCTION

THEIR MANUFACTURE AND PROPERTIES

BY THE LATE
PROFESSOR ADELBERT P. MILLS
OF CORNELL UNIVERSITY

SECOND EDITION, EDITED BY

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TOTAL ISSUE, TEN THOUSAND

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PREFACE TO SECOND EDITION

No attempt has been made in this book to change fundamentally the original work of Professor Mills which has proved of great value to students and engineers.

Certain chapters have been condensed, parts of others have been re-written. Several new chapters have been added. The book has also been divided into sections.

Acknowledgment is made to the following members of the faculty of the Massachusetts Institute of Technology for their valuable advice and assistance:

Professor Henry Fay, who reviewed the chapter on Steel; Professor R. S. Williams, who reviewed the chapter on Non-Ferrous Metals and Alloys; Professor I. H. Cowdrey, who reviewed the chapters on Stone and Timber; Professor G. B. Haven, who prepared the new chapter on Mechanical Fabrics; and Mr. Dean Peabody, Jr., who re-wrote the chapter on Concrete.

Acknowledgment is also made to the Plymouth Cordage Company and John A. Roebling's Sons Company for information furnished on fibre and wire rope.

H. W. Hayward

Cambridge, Mass.
December, 1921

PREFACE TO FIRST EDITION

THIS work is an outgrowth of certain lectures and notes which have been used in the author's classes in the College of Civil Engineering, Cornell University, for the past several years. Its preparation was undertaken to meet the need which was felt for a general text-book covering the manufacture, properties, and uses of the more common materials of engineering construction in a comparatively concise and thoroughly modern manner.

Although this book is intended primarily for use as a text-book of somewhat elementary character and is not a treatise exhaustively covering the very broad field of "Materials of Construction," the treatment has been made more detailed in some respects than may be necessary for class-room purposes, and its applications as a general reference work thereby broadened.

The treatment of the various classes of materials considered follows a general systematic form which has been made uniform throughout so far as has been found practicable. The consideration of each material or class of materials is prefaced by a discussion of its ordinary applications in engineering construction, followed by a study of its manufacture or natural occurrence, and concluded by a discussion of physical and mechanical properties in their relation to its uses.

As a result of the author's experience in the teaching of this subject, the properties exhibited by a given material are, for the most part, considered as dependent phenomena closely related to certain more or less variable factors connected with the process of manufacture, natural occurrence, and conditions of service or testing, and not as independent qualities inherent in that material. It has been considered advisable to avoid the inclusion of tabulations of investigational data whenever the data could be presented graphically by curves or diagrams; discussions of conflicting empirical data on points admitting of controversy have been reduced to a minimum; and an effort has been made to present the material in a definite, concrete form, the necessity for the exercise of discriminative judgment upon the part of the student being obviated by conclusions drawn by the author, even though it is recognized that in so doing errors of judgment may be made, and the criticism of those who object to any form of dogmatic statement is invited.

The subject of testing materials has not been covered, except in so far as methods of testing are inseparable from discussions of the properties of materials revealed by laboratory tests. It is the author's conviction that this subject can be handled only in the laboratory itself, and the place for such material is therefore in a laboratory manual. It is assumed, however, that a laboratory course in testing materials will invariably parallel and supplement the text-book course in the study of materials.

The author cannot make a pretense of being a specialist in all of the fields which are covered in the various chapters of this book, and this work is therefore to a very large degree a compilation of data and opinion from a great many different sources. The author takes pleasure in acknowledging his great indebtedness to the large number of engineers and manufacturers who have privately or by their writings contributed much to make up this volume. A large number of technical books which are devoted to the consideration of some part of the ground covered by this text have been frequently consulted and freely used. An effort has been made to always acknowledge the source of information so obtained, and if any error of omission has been committed in this respect, it has been committed inadvertently, not by intention.

The following well-known text-books and reference works have been most frequently used:

" Cements, Limes, and Plasters," by E. C. Eckel; " Portland Cement," by R. K. Meade; " Manufacture of Portland Cement," by R. C. H. West; " Masonry Construction," by I. O. Baker; " Stone for Building and Decoration," by G. P. Merrill; " Building Stones and Clay Products " and " Economic Geology," by Heinrich Ries; " The Blast Furnace and the Manufacture of Pig Iron," by Robert Forsythe; " The Metallurgy of Iron and Steel," by Bradley Stoughton; " The Metallurgy of Steel " and " Iron, Steel, and Other Alloys," by H. M. Howe; " The Manufacture and Properties of Iron and Steel," by H. H. Campbell; " Iron and Steel," by H. P. Tiemann; " Modern Iron Foundry Practice," by G. R. Bale; " Cast Iron," by W. J. Keep; " The Production of Malleable Castings," by Richard Moldenke; " The Corrosion and Preservation of Iron and Steel," by A. S. Cushman and H. A. Gardner; " The Metallography of Iron and Steel," by Albert Sauveur; and " Economic Woods of the United States " and " The Mechanical Properties of Wood," by S. J. Record.

The following periodicals and publications of various societies have also been frequently consulted:

"Engineering News," "Engineering Record," "Metallurgical and Chemical Engineering," Proceedings of the American Society for Testing Materials, Proceedings of the International Association for Testing Materials, Transactions of the American Society of Civil Engineers, Proceedings of the Institution of Mechanical Engineers, Journal of the Iron and Steel Institute, "Tests of Metals," published annually by the U. S. War Department, "Mineral Resources," published annually by the U. S. Geological Survey, Reports of the various State Geological Surveys, the publications of the Forestry Division of the U. S. Department of Agriculture, and the publications of the U. S. Bureau of Standards.

ADELBERT P. MILLS.

ITHACA, N. Y.
February 20, 1915.

TABLE OF CONTENTS

SECTION 1

PLASTER, LIME, NATURAL CEMENT

SECTION 2

PORTLAND CEMENT AND CONCRETE

SECTION 3

STONE

SECTION 4

BRICKS AND OTHER CLAY PRODUCTS

SECTION 5

THE FERROUS METALS

SECTION 6

THE NON-FERROUS METALS AND ALLOYS

SECTION 7

TIMBER

SECTION 8

ROPE

SECTION 9

MECHANICAL FABRICS

MATERIALS OF CONSTRUCTION

SECTION 1

CHAPTER I

GYPSUM PLASTERS

1. Definition and Classification. Gypsum plasters comprise all that class of plastering and cementing materials obtained by the partial or complete dehydration of natural gypsum, and to which certain materials which serve as retarders or hardeners, or which impart greater plasticity to the product, may or may not have been added during or after calcination. Gypsum plasters may be classified as follows: *

(*A*) Produced by the incomplete dehydration of gypsum, the calcination being carried on at a temperature not exceeding 190° C. (374° F.).

Plaster of Paris, produced by the calcination of a pure gypsum, no foreign materials being added either during or after calcination.

Cement Plaster (often called *Patent* or *Hard Wall Plaster*), produced by the calcination of a gypsum containing certain natural impurities, or by the addition to a calcined pure gypsum of certain materials which serve to retard the set or render the product more plastic.

(*B*) Produced by the complete dehydration of gypsum, the calcination being carried on at temperatures exceeding 190° C. (374° F.).

Flooring Plaster, produced by the calcination of a pure gypsum.

Hard Finish Plaster, produced by the calcination, at a red heat or over, of gypsum to which certain substances (usually alum or borax) have been added.

2. Gypsum Rocks. Pure gypsum is a hydrous lime sulphate ($CaSO_4 + 2\,H_2O$), the composition of which by weight is:

---

* Eckel, "Cements, Limes, and Plasters."

Lime Sulphate ($CaSO_4$)	Lime (CaO)...........32.6%	79.1%
	Sulphur trioxide (SO_3)..46.5	
Water (H_2O)..		20.9
		100.0%

Natural deposits of gypsum are practically never pure, the lime sulphate being adulterated with silica, alumina, iron oxide, calcium carbonate, and magnesium carbonate. The total of all impurities varies from a very small amount up to a maximum of about 6 per cent.

The physcial form of a natural gypsum is usually that of a *massive* rock formation. It also occurs as an *earthy gypsum* or *gypsite*, and as *gypsum sands* in some localities. *Alabaster* is a specially pure white massive gypsum of very even texture and fine grain, and *selenite* is a white semi-transparent crystalline gypsum which occurs only in relatively small deposits in massive gypsum.

3. Theory of Calcination. If pure gypsum be subjected to any temperature above 100° C. (212° F.), but not exceeding 190° C. (374° F.), three-fourths of the water of combination originally present is driven off. The resultant product is called *Plaster of Paris* ($CaSO_4 + \frac{1}{2} H_2O$). Since the time required for the process is directly dependent upon the temperature maintained, it is the general practice to keep the temperature near the highest possible limit, thus effecting an economy in both time and fuel. Plaster of Paris readily recombines with water to form gypsum, hardening in a very few minutes.

If the gypsum be calcined at temperatures much above 190° C. (374° F.) it loses all of its water of combination, becoming an anhydrous sulphate of lime ($CaSO_4$). All temperatures exceeding that required for complete dehydration result in some impairment, temporary or permanent, of the capacity of the plaster for recombination with water, the extent of the injury being dependent upon the intensity and the time of the heating and upon the state of subdivision of the material. If the material is finely divided, the plaster may be made totally incapable of recombining with water (dead-burnt plaster). If the material is calcined in a lumpy condition the temperature not exceeding 500° C. (932° F.) and not prolonged beyond three or four hours, the principal effect upon the product is a great retardation of the rate of setting and hardening, a hydrate being ultimately formed, in the course of days or weeks, which greatly exceeds ordinary plaster in hardness and strength.

4. Practice of Calcination. Plaster of Paris and cement or hard wall plasters are made in a practically identical manner, the distinct properties of the two materials being due to the use of pure gypsum in the one case, and impure gypsum or adulterated pure gypsum in the other.

Two operations only are involved in the process of manufacture: crushing and grinding, and calcination. Rock gypsum is first crushed to fragments about one inch in diameter which are passed through an intermediate crusher and then pulverized in a finishing mill.

Plaster is calcined in kettles or rotary kilns.

The kettle is a cylindrical steel vessel, 8 to 10 feet in diameter and 6 to 9 feet high (Fig. 1), mounted upon a masonry foundation. The bottom is convex, rising about 1 foot in the center, and made of cast iron. A masonry wall encloses the steel cylinder, leaving an open annular space between for the circulation of heat. A fire is maintained on grates below the kettle, and the heated gases pass through ports into the open annular space, then through the kettle in horizontal flues and out through the stack. A central vertical shaft propels paddles just above the bottom, thus keeping the material agitated and preventing the burning out of the bottom.

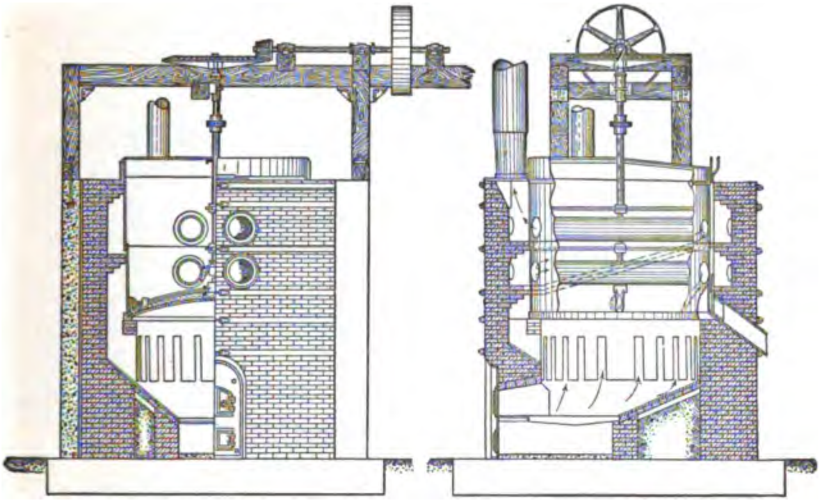

FIG. 1. — Four Flue Plaster Calcining Kettle.

The charge, consisting of 7 to 10 tons of ground gypsum, is delivered by a chute to the charging door provided in the sheet-iron cap of the kettle. Heat is gradually applied as the charge is slowly fed in and, as the temperature rises after charging is complete, the contents boil violently until the mechanically held water is driven off. Boiling is renewed again when the water of combination begins to be driven off, and continues until the end of the process. The kettle is discharged by blowing out through a small gate in the lower part of the side of the shell.

When the rotary calciner (Fig. 2) is employed the raw material is used in the condition in which it comes from the intermediate crusher, and feeding from the supply bin is continuous.

The cylinder is set on a slight incline, and the lumpy material fed in at the upper end gradually traverses its length as the cylinder slowly rotates, is discharged at the lower end, and enters calcining bins which are lined with non-absorptive brick, and from which outside air is excluded. The cylinder is enclosed within a brick chamber which includes a firebox at one end, and a considerable air space is provided between the steel shell and the masonry. The hot furnace gases are drawn into the brick chamber by a fan and there mixed with sufficient air, admitted from the outside, to secure the desired temperature. These gases are drawn into the cylinder through hooded openings provided at intervals, and pass through it in a reverse direction to that taken by the material. A dust chamber provided between the cylinder and the stack catches the most finely ground plaster which has been carried off in suspension by the gases.

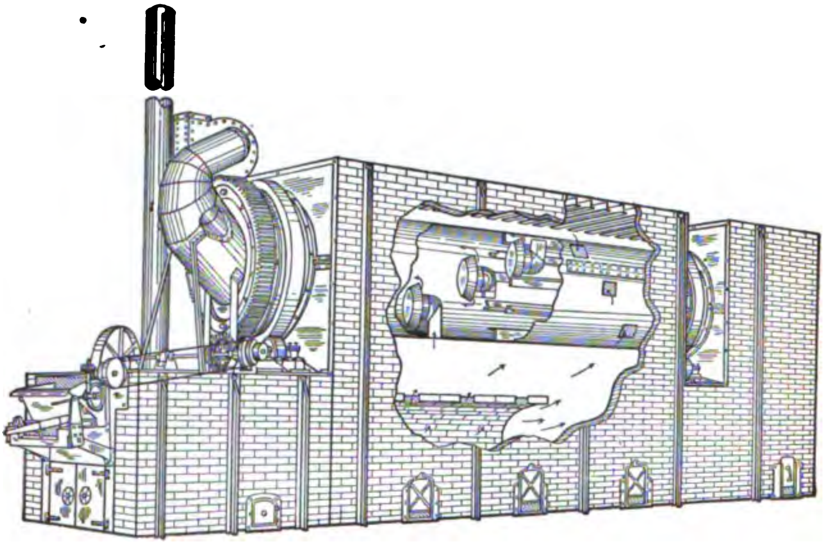

Fig. 2. — Rotary Cylinder Type of Plaster Calciner.

The heat attained in the rotary calciner is from 200° C. (392° F.) to 300° C. (572° F.), but time does not suffice for the complete dehydration of the gypsum, and the removal of combined water is completed in the calcining bins through the agency of the residual heat of the material itself. After about thirty-six hours the process will be completed. Air inlets are then opened and the contents of the bin are rapidly cooled. By providing four bins for each calciner the process is made continuous; while one bin is being charged, the process of calcination is being completed in the second and third bins, and the fourth is being discharged. The product of the calcining bins is conveyed to finishing mills and there pulverized to the form of the marketable article.

Many cement or hard wall plasters are made direct from earthy gypsum or gypsite, which is often found to contain a suitable percentage of foreign material of such character that no corrective material need be added either to retard the set or impart plasticity.

Flooring plaster is produced by the calcination of a pure gypsum in a lump form in a vertical separate-feed kiln which differs little from the separate-feed kiln used for the calcination of lime. The fuel, burned on grates outside the kiln, does not come in contact with the gypsum, but the hot gaseous products of combustion pass directly through it, heating it to a temperature of from 400° C. (752° F.) to 500° C. (932° F.). Higher temperatures, or prolongation of heating beyond three or four hours, ruin the plaster by robbing it of its setting properties as above noted. Fine pulverization of the plaster must follow calcination.

A well-known variety of hard-finish plaster is the so-called *Keene's cement.* This plaster is produced by the double calcination of a very pure gypsum. After the lump gypsum has been calcined at a red heat, the resulting anhydrous lime sulphate is immersed in a 10 per cent alum solution, then recalcined, and finally pulverized in a finishing mill.

5. Additions Subsequent to Calcination. Plaster of Paris is never adulterated in any way during manufacture, but cement or hard wall plasters often require the addition of a retarder to render them sufficiently slow setting. The retarders commonly used are organic materials, such as glue, sawdust, blood, packing-house tankage, etc. As a rule the amount of retarder required does not exceed 0.2 per cent. Certain very impure gypsums produce a plaster which is too slow setting, or sometimes extreme rapidity of set is required. In such instances the addition of an accelerator is necessary. The materials used for this purpose are crystalline salts, common salt ($NaCl$) being one of the best.

Gypsum plasters destined for use as wall plasters must usually have their plasticity enhanced by the addition of some material such as clay or hydrated lime, through the agency of which the naturally "short," non-plastic material is greatly improved in working qualities and sand-carrying capacity. With the exception of those plasters which are made from earthy gypsum which naturally contain 20 per cent or more of clay, it is the usual practice to add about 15 per cent of hydrated lime or, less frequently, clay, to the calcined plaster. Greater cohesiveness may also be imparted to wall plasters by the addition of finely picked hair or shredded wood fiber.

No additions are made to flooring plaster subsequent to calcination. Keene's cement is treated with an alum bath as above noted. Mack's cement, another variety of hard-finish plaster, is made by the addition to dehydrated gypsum (flooring plaster) of 0.4 per cent of calcined sodium sulphate (Na_2SO_4) or potassium sulphate (K_2SO_4).

PROPERTIES AND USES OF GYPSUM PLASTERS

6. Setting and Hardening.* The setting of plaster of Paris and other gypsum plasters is a process of recombination of the partially or totally

---

* By the term "setting" is meant the initial loss of plasticity, while "hardening" means the subsequent gain in ability to resist indentation or abrasion.

dehydrated lime sulphate with water to reform hydrated lime sulphate or gypsum. A pure plaster of Paris sets in from five to fifteen minutes after the addition of water. Plasters made from impure gypsum are less quick setting, requiring from one to two hours, and the completely dehydrated classes of plasters are very slow setting, whether adulterated or not. The ultimate degree of hardness attained by impure cement or hard wall plasters greatly exceeds that of pure plaster of Paris, and the hard-burned plasters are hardest of all.

7. Strength of Plasters. Trade conditions in the plaster industry have not yet reached the point where contracts for plasters are made contingent upon their satisfactorily meeting the requirements imposed by a series of physical and mechanical tests. In consequence, scientific investigation of the properties of plasters has been undertaken to a very limited extent, and the value of the data which bear upon the question is impaired by the fact that methods of examination have not been standardized.

The tensile strength of plasters is dependent upon so many considerations incidental to methods and conditions of testing that little data as to tensile strength in general will be introduced. Tests made at Washburn College show that the tensile strength of neat plaster is probably between 400 and 600 pounds per square inch.

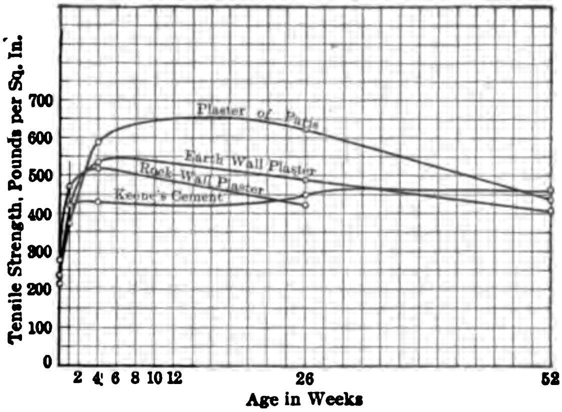

FIG. 3. — Tensile Strength of Neat Wall Plasters.

The gain in strength is very rapid for the first few days and the maximum strength is attained in a few weeks, after which retrogression in strength usually occurs.

Tests made at Iowa State College indicate that the tensile strengths of mortars made of sand and plaster are as follows:

Parts plaster	Parts sand.	Per cent of strength of neat plaster.
1	1	85
1	2	55
1	3	33

The strength of mortar is largely dependent upon the character of the sand used. Mortar made from fine plaster is somewhat stronger than that made from plaster not sifted.

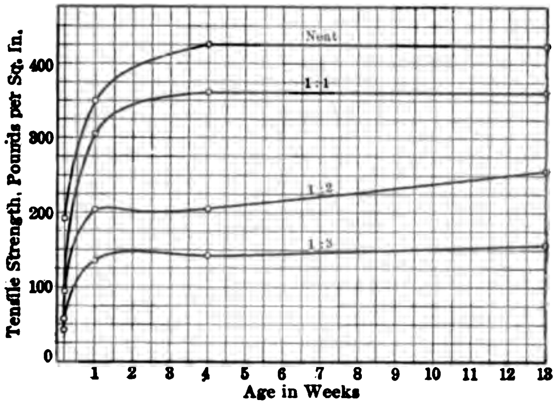

FIG. 4. — Comparative Tensile Strength of Neat Plaster and Various Mortars.

A tentative standard offered by the Am. Soc. for Testing Materials suggests that neat gypsum plaster shall set in not less than 1½ hours and shall have a tensile strength of not less than 150 pounds per square inch.

The compressive strength of plasters is dependent upon practically the same factors as the tensile strength, but the experimental determination of compressive strength is influenced to so large an extent by the personal factor in making and testing specimens, that satisfactory experimental data are almost entirely lacking. The average compressive strength of neat plaster varies between 1000 and 2500 pounds per square inch, and the strength of one to two sand mortar is about three-fifths of the neat strength.

8. Uses of Various Gypsum Plasters. Plaster of Paris, because of the extremely rapid set which especially fits it for various special uses as a casting plaster, etc., finds very little application as a material of engineering construction. Almost its only structural use is in the form of molded ornaments of "stucco" which serve as architectural adornment of buildings. Plaster of Paris is not adapted for use as either a wall plaster or a mortar for masonry construction unless additions be made to retard its set and make it more workable. If this is done, however, it is no longer called plaster of Paris, but becomes a cement or hard wall plaster.

Cement or hard wall plasters find their principal applications as wall plasters with which a certain amount of hair, wood fiber, or asbestos fiber, together with hydrated lime or clay, has been mixed at the place of manufacture. Gypsum wall plasters possess certain advantages over ordinary lime plasters, but also suffer by comparison with lime plasters in other respects.

Among the advantages of gypsum plasters, is the fact that the material comes upon the work ready to be mixed with sand and water and immediately applied to the lath, whereas quicklime requires careful slaking and should be allowed to season before being made up in a mortar and applied to the walls. Gypsum plasters set more rapidly and dry out in a much shorter time than do lime plasters, thus often avoiding a delay in the completion of the interior finish of buildings. On the other hand, no gypsum product makes as plastic and smooth working a plaster as does the best lime, provided the latter is properly slaked, seasoned, and mixed. Lime plasters excel in sand-carrying capacity, making it possible to use three or four parts of sand to one of lime for the first or "scratch" coat on walls, and two parts of sand to one of lime for the second or "brown" coat, whereas it is inadvisable with most gypsum plasters to use mortar mixtures leaner than 1 : 2 for either scratch or brown coat on account of their poor spreading qualities. The finish or "skim" coat is a neat or nearly neat paste in either case.

Among the other applications of hard wall plaster the following are worthy of brief notice: Mixed with finely ground cinders and water to form a fluid mix, hard wall plaster is poured in forms for floor panels of buildings. Mixed with sawdust it is molded into blocks which may be nailed in place as a wall finish, and, without the sawdust it may be molded into solid or hollow building blocks and tiles for the construction of partition walls and floors and for fireproofing. Another application of cement plaster is in the construction of "plaster-board," wherein the plaster is laminated with thin layers of card-board or wood in sheets which are ready to be nailed to the studding of partition walls. The wall surface thus provided is subsequently plastered, as a rule, but may be finished in panels with no additional plaster by simply covering the joints with wood strips.

Flooring plaster is, as the name implies, intended primarily as a surface finish for floors. It must be protected from moisture while setting, and must dry evenly to avoid the formation of cracks. After standing about twelve hours it is pounded with wooden mallets and smoothed with trowels.

Hard-finish plasters find their principal application as wall plasters and as floor surface, one of the most common applications being as an imitation of tiling or marble for floors and wainscoting in hospitals, lavatories, etc. Keene's cement is, perhaps, the best known variety of hard-finish plaster. Its set is extremely slow, and it gains in strength very gradually, but ultimately attains a great degree of hardness and a strength exceeding that of any ordinary gypsum plaster. It may be regaged with water after having become partially set, and will then take its set and harden just as satisfactorily, apparently, as if the process of hardening had not been interrupted.

CHAPTER II

QUICKLIME

9. Definition and Classification. Quicklime is the name applied to the common or commercial form of calcium oxide (CaO), obtained by the calcination of a stone in which the predominating constituent is calcium carbonate ($CaCO_3$), often replaced, however, to a greater or less degree by magnesium carbonate ($MgCO_3$), this product being one which will slake on the addition of water.

Hydrated lime is the same material as quicklime except that it does not possess the power of slaking, since it has been chemically satisfied with water during manufacture.

Quicklime is divided into two general grades:

Selected. A well-burned lime, picked free from ashes, core, clinker, or other foreign material, containing not less than 90 per cent of calcium and magnesium oxides and not more than 3 per cent of carbon dioxide.

Run-of-kiln. A well-burned lime without selection, containing not less than 85 per cent of calcium and magnesium oxides and not more than 5 per cent of carbon dioxide.

According to the physical form of the material, quicklime is marketed as:

Lump Lime. The size in which it comes from the kiln.

Pulverized Lime. Lump lime reduced in size to pass a ¼-inch screen.

According to relative content of calcium oxide and magnesium oxide, quicklimes are divided into four types:

High-calcium. Quicklime containing 90 per cent or over of calcium oxide. (Sometimes termed "rich," "fat," or "caustic" lime.)

Calcium. Quicklime containing not less than 85 per cent and not more than 90 per cent of calcium oxide.

Magnesium. Quicklime containing between 10 and 25 per cent of magnesium oxide.

High Magnesium or *Dolomitic.* Quicklime containing over 25 per cent of magnesium oxide.

10. The Place of Lime Among Cementing Materials. Cementing materials used structurally may be divided into two general classes, as *non-hydraulic* and *hydraulic.* Lime is the most common non-hydraulic cementing material. The hydraulic cements include hydraulic limes, grappier cements, natural cements, Portland cement, and puzzolanas.

11. Structural Uses. Lime is used in combination with sand as a mortar for laying brick and stone masonry, as a wall plaster, and in gaging cement mortars for the purpose of increasing their plasticity, or to reduce their permeability.

MANUFACTURE OF LIME

12. Limestone Rocks. An ideal, pure limestone consists entirely of calcium carbonate ($CaCO_3$) which, at a temperature of 900° C. (1652° F.) or over, becomes dissociated, the carbon dioxide (CO_2) being driven off as a gas, leaving behind a white solid, calcium oxide or quicklime (CaO).

As pure calcium carbonate consists of 56 parts by weight of CaO to 44 parts of CO_2, the theoretical proportion of quicklime obtainable by the calcination of limestone will be 56 per cent by weight.

In practice, the proportion of quicklime will always fall below this theoretical limit on account of the inevitable presence of impurities in the limestone and the imperfections of the process of calcination.

Limestones encountered in practice depart more or less from this theoretical composition. Part of the lime is almost invariably replaced by a certain percentage of magnesia (MgO), making the stone to a greater or less extent a magnesian limestone. In addition to magnesia, silica, iron oxide, and alumina are usually present and, to a slight extent, sulphur and alkalies.

13. Theory of Calcination. The burning or calcination of lime accomplishes three objects.

The water in the stone is evaporated.

The limestone is heated to the requisite temperature for chemical dissociation.

The carbon dioxide is driven off as a gas, leaving the oxides of calcium and magnesium.

The evaporation of any water present in the stone means that a certain portion of the heat supplied during calcination does not directly assist in the dissociation of the carbonates. This heat does not mean a thermal loss, however, because the presence of the water, and the steam generated from it, facilitates the dissociation process.

The temperature of dissociation of pure calcium carbonate at a pressure of one atmosphere has been determined by Johnson to be 898° C. (1650° F.), and the corresponding temperature for magnesium carbonate somewhat lower.

Theoretically, all limestones could be properly burned at a temperature of about 880° C. (1600° F.), provided sufficient time was allowed. In practice, however, the maximum kiln output is always striven for, and, since the rate of heating is directly proportional to the temperature of the kiln, the maximum kiln output is obtained by burning at the highest possible temperature. The highest temperature practicable is not the highest temperature attainable, however, because the increased activity of the impurities with rising temperature set a very definite maximum limit, the exceeding of which means serious injury to the quality of the lime produced.

The impurities in limestones readily combine with the basic lime and magnesia. The silica forms silicates, the alumina forms aluminates, and the iron oxide forms ferrites. These silicates, aluminates, and ferrites are all readily fusible compared with pure lime or magnesia, and the result of their formation is a softening of the portion of the stone thus rendered fusible at the practical dissociation temperature, and its softening envelopes the particles of lime with a slag-like coating which causes the quicklime to slake with difficulty. The softening of the mass also results in compacting the material, thereby further injuring its qualities by mechanically rendering it less porous.

This behavior on the part of the impurities explains the existence of maximum practical temperature limits in burning impure limestones, exceeding which causes marked loss of power of the quicklime to combine with water in slaking, whereas it is practically impossible to overburn pure limestone.

The physical character of the limestone has an important bearing upon the burning temperature, quite aside from the question of chemical composition. A naturally coarse, porous stone is much more rapidly acted upon by heat than a dense, finely crystalline stone, and in consequence may be burned more rapidly and at a lower temperature. Small pieces of stone may also be burned more readily than large stones. Large sizes seem to be preferred, however, by the practical lime manufacturer, the common practice being to use "stones" measuring about 8 to 10 inches in diameter.

Provision must be made for carrying off the carbon-dioxide gas evolved during calcination. If this gas is allowed to accumulate, it may recombine with lime and magnesia and reform their carbonate. This phenomenon is known technically as "recarbonating."

14. Practice of Calcination. The types of kilns employed in lime burning may be described as follows:

Intermittent Kilns. An early form of intermittent kiln consisted simply of a domelike structure crudely constructed by using the larger blocks of the stone to be burned.

The balance of the limestone was piled on top and a wood fire started underneath. A bright red heat having been obtained throughout the mass of stone, this temperature was maintained for a period of three or four days, when, the mass having become soft, the fire was allowed to go out and, after cooling, the lime was removed, the structure being demolished in so doing.

Permanent intermittent kilns, often called "pot kilns" (Fig. 5), built of stone with a firebrick lining and provided with a grate upon which the fuel is placed, gradually replaced the original type. These kilns are provided with an arched opening at the bottom through which fuel is introduced and the burnt lime removed. The fuel consumption of even this type of intermittent kiln is very excessive, due to the necessity of heating the entire mass of masonry, as well as the contents, to the required temperature of calcination each time the kiln is charged. In addition, the product is never uniformly burned.

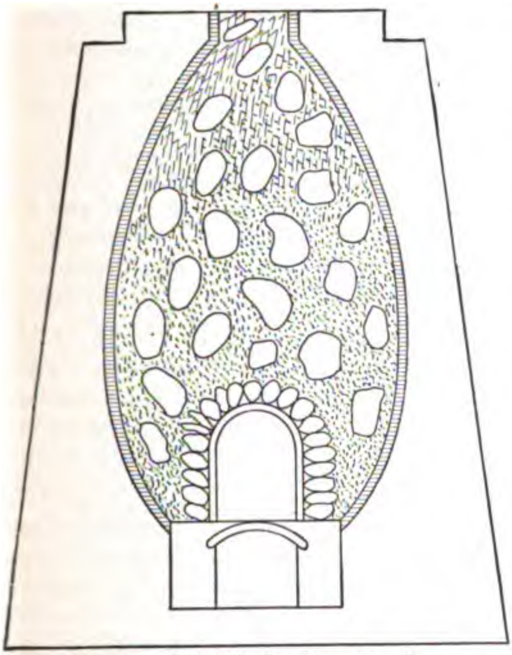

FIG. 5. — Pot Kiln for Lime Burning.

Continuous Kilns. *The Vertical Kiln with Mixed Feed.* In this kiln, the fuel and the limestone are charged in alternate layers, the lime being removed at the bottom while fresh fuel and limestone are charged in at the top.

The Vertical Kiln with Separate Feed. The kilns of this type (Fig. 6) are so designed that the fuel and limestone do not come in contact, the fuel being burned in separate fireplaces either set in the wall of the kiln or outside the kiln shell. The limestone therefore comes in contact only with the hot gaseous products of combustion.

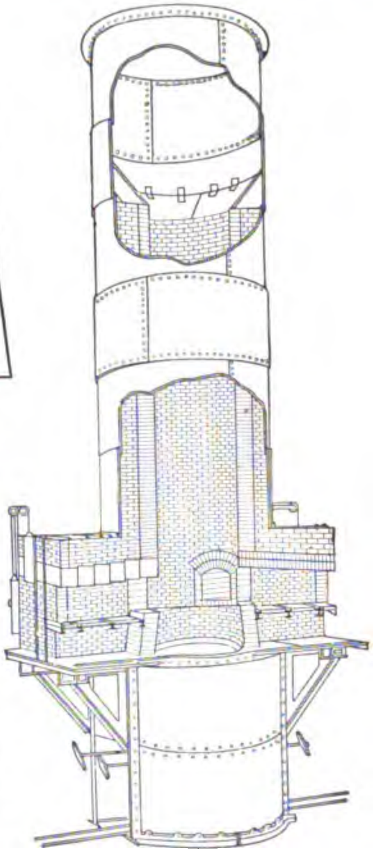

FIG. 6. — Keystone Separate-feed Lime Kiln.

The relative advantages of these two types, which are almost exclusively used in the United States, may be summarized as follows: The mixed-feed kilns are cheaper to construct, somewhat more economical of fuel, and somewhat more rapid in operation. On the other hand, the separate-feed kilns yield a lime somewhat less discolored by contact with the fuel, the lime is free from the fuel ash, which is not easily separated out, and the danger of some part of the lime being imperfectly calcined, owing to a coating of fuel clinker on the lumps, is obviated. From 75 to 80 per cent of the output of the mixed-feed kiln is marketable as well-burned, clean, white lime as compared with 90 per cent obtainable from separate-feed kilns.

Ring or Chamber Kilns. **The ring kiln has been used quite extensively in Europe, but has never come into favor in the United States. The commonest type of ring kiln, the Hoffman kiln, consists of a series of chambers arranged around a central stack. Each chamber is connected by flues with the stack and with each of the two adjoining chambers, and each flue is provided with a damper by means of which the passage may be closed. The chambers may be charged with limestone and fuel in the shape of fine coal, and one chamber is fired. The dampers are now so set that the hot gases of the burning chamber must traverse all the other chambers before passing to the stack, so utilizing the heat of the gases in preheating the contents of the chambers not yet fired. When the calcination of the limestone in the first chamber is complete, the second chamber is fired and the first chamber is temporarily cut out of the circuit until it has been discharged and recharged, when it becomes the last chamber in the circuit. The operation is continued in this manner indefinitely.**

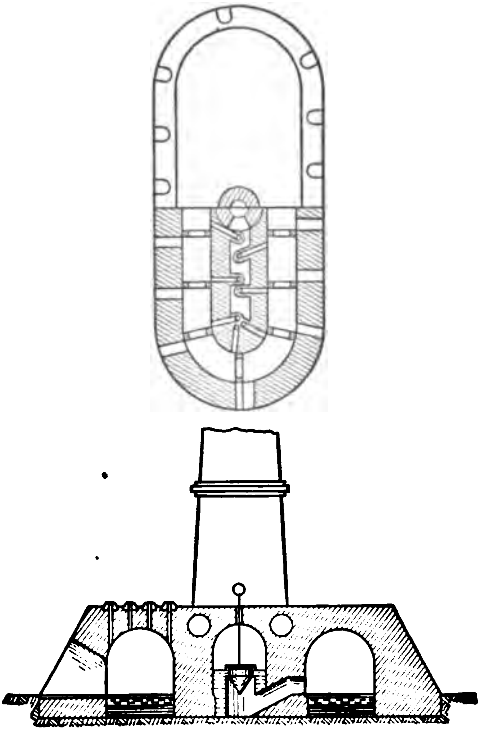

FIG. 7 — Hoffman Ring Kiln.

Rotary Kilns. **Rotary kilns have been applied to the calcination of lime to a limited extent. They are subject to the disadvantage of requiring that the stone be finely crushed prior to the calcination, and the product is consequently so finely divided that it is not marketable as lump lime, but can be sold only after grinding or hydrating, as either ground or hydrated lime.**

The fuels used in lime burning are wood, bituminous coal, and producer gas. Wood fuel possesses a distinct advantage over coal because of its longer flames and consequent better heat distribution throughout the mass of stone. Coal would never be used as a kiln fuel were it not for the impossibility of procuring wood in many districts. The short-flaming hot coal fire results in overheating of the portion of the kiln near the firebox, while the material shortly above the fire zone receives far too little heat. The use of producer gas as a fuel for lime burning is a late development, its installation having thus far been largely confined to the larger and more modern plants.

A lime kiln in operation always contains three classes of material: (*a*) Stone undergoing preliminary heating through the agency of the escaping hot products of combustion: (*b*) Stone undergoing dissociation through the agency of the direct heat of the fuel: (*c*) Calcined lime which accumulates in the lower portion of the kiln and is withdrawn in part from time to time. The total amount of lime present in the kiln cannot be drawn at one time, because, aside from the desirability of letting it cool in the kiln itself, enough must remain at all times to fill the "cooler" (that portion of the kiln below the level of the fuel grate), thus preventing unburned stone from sinking below the level of the zone in which it is subjected to the action of the flames of the fires.

The operation of drawing consists in opening a draw-door provided in the lower part of the cooler, poking the lime loose with a bar, and allowing it to fall into a barrow or car placed underneath. This operation is repeated at intervals of from 4 to 6 hours.

15. Treatment Subsequent to Calcination. Lime drawn cold from the kiln is immediately ready to be marketed as lump lime. When the kiln is not provided with a cooler, however, or when drawn from the cooler while still very hot, it is necessary to spread it out on a cooling floor or leave it standing in fireproof containers for a few hours before taking it to storage, packing house, or cars. Underburned and overburned material is easily recognized by its appearance, and is sorted out while drawing it into the barrows, or while it lies on the cooling floor.

A large proportion of the lime intended for use in the building trades, especially as hydrated lime, as well as for agricultural purposes and many applications in the arts and industries, is now ground before being marketed. Ground lime is prepared by running the cooled lime through a crusher and then a pulverizing mill, which reduces it to a size sufficient to pass a sieve of 80 meshes per linear inch. The product is then barreled or sent to the hydrator. Ground lime used structurally as quicklime is seldom crushed to a size less than about ½ inch.

PROPERTIES AND USES OF QUICKLIMES

16. Classification of Limes.* Limes may be conveniently classified according to the purposes for which they are used, as agricultural limes, chemical limes, building limes, and finishing limes.

For agricultural limes only the chemical composition is of importance; for limes used in the chemical industries the chemical composition and the rate of hydration are important; building limes must be satisfactory as regards sand-carrying capacity, yield of lime-paste per unit weight of lime and strength; and finishing limes must be satisfactory with respect to rate of hydration, plasticity, sand-carrying capacity, color, yield, waste, hardness, time of setting, and shrinkage.

17. Chemical Composition. The approximate chemical composition of limes of various classes has been indicated in Art. 9, wherein limes were classified and graded according to their content of calcium oxide, magnesium oxide, and carbon dioxide. The following table illustrates the range of composition found for limes of various classes upon analysis of samples of quicklimes coming from many parts of the United States:

ANALYSIS OF QUICKLIMES

Class of lime.	High calcium quicklimes.			Calcium and Magnesian quicklimes.			Dolomitic quicklimes.		
Component.	Min. per cent.	Max. per cent.	Ave. of (10) per cent.	Min. per cent.	Max. per cent.	Ave. of (6) per cent.	Min. per cent.	Max. per cent.	Ave. of (2) per cent.
SiO_2	0.33	2.20	0.81	0.66	9.00[1]	3.12	0.14	1.59	0.87
Fe_2O_3	0.08	0.43	0.23	0.17	0.59	0.41	0.19	0.39	0.29
Al_2O_3	0.02	0.42	0.22	0.18	2.57[1]	0.93	0.14	0.49	0.32
CaO	91.37	98.08	94.98	78.59	84.81	81.42	55.80	64.45	60.13
MgO	0.17	4.55	1.39	1.03	16.83	9.26	31.61	40.62	36.12
H_2O	0.36	3.45	1.66	0.63	12.42[2]	4.18	0.55	1.56	1.06
CO_2	0.20	1.84	0.83	0.24	1.94	0.18	0.35	3.01	1.68

[1] Excessively high in acid impurities. [2] Incipient air-slaking shows.

18. Hydration or Slaking. Quicklime intended for use in mortars for masonry construction or as a wall plaster must first be prepared for mixing with water to form a lime paste by being slaked. The hydration or slaking of quicklime consists in the addition of sufficient water for the formation of calcium hydroxide, the operation being represented by the formula:

$$CaO + H_2O = Ca(OH)_2,$$
$$75.7 + 24.3 = 100 \text{ (parts by weight).}$$

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* This classification is that proposed by W. E. Emley of the Pittsburgh Branch of the U. S. Bureau of Standards.

If the quicklime were absolutely free from impurities the amount of water required for complete slaking would equal 32.1 per cent by weight of the quicklime, but the fact that the quicklime is always impure to a greater or lesser degree makes the amount of water actually required less than this. The formation of lime hydrate is attended by the evolution of considerable heat and an expansion to about 2½ or 3 times its former volume. Magnesian quicklimes, and particularly dolomitic quicklimes, slake more slowly than high calcium limes, and the slaking is attended with the evolution of much less heat and far less expansion. The fact that quicklime used in the building trades is often slaked carelessly by unskilled labor has caused a demand for "hydrated lime."

Lime intended for use in a mortar is usually slaked in a mortar mixing box, the mixture being stirred as water is added until a thin paste or "putty" has been formed. The putty is then covered with sand to protect it from the action of the air.

Lime paste or putty designed for use as a plaster should be allowed to season for several weeks before being used.

The reaction involved in the hydration of quicklime may result in the production of either crystalline calcium hydroxide or colloidal calcium hydroxide, the relative quantity of one or the other being dependent upon the time afforded for the reaction. Crystals of calcium hydroxide form and grow slowly, whereas the colloidal hydroxide forms with great rapidity. Consequently, the more rapid the reaction is made to be, the greater the proportion of colloidal hydroxide. The reaction may be most readily hastened by using warm water in slaking. A preponderance of colloidal hydroxide is eminently desirable from the standpoint of the mason who judges a mortar by its plasticity or spreading qualities, its yield, and its sand-carrying capacity.

The hydration of high-calcium quicklimes is attended by great danger of "burning," due to too great a rise in temperature. "Burned lime," appears to be chemically inert and is useless in a mortar or plaster. Burning may best be avoided by securing an intimate contact between every particle of lime and the water. Great watchfulness and continuous stirring of the mixture are therefore necessary.

No danger of burning attends the slaking of most magnesian and all dolomitic quicklimes. On the contrary, the danger in this case is that the quicklime may never be properly slaked before being used, as all magnesian quicklimes slake very slowly.

"Air-slaked" lime is a very different thing from the ordinary slaked lime. Quicklime exposed to the air absorbs moisture and becomes slaked lime, the expansion accompanying hydration causing the lumps to fall into a more or less fine powder. Immediately, the slaked lime is attacked by the carbon dioxide of the air, and the resulting product is simply powdered calcium carbonate, $CaCO_3$. The term "air-slaked" will be seen to be a very misleading one, for the quicklime has not only been slaked by the moisture in the air, but has been ruined completely as a cementing material by taking up carbon dioxide while in a loose powdered state. The fact that quicklime does "air slake" when exposed to the air is not an unmitigated evil, however, because it renders possible the storage and even the shipment of ground lime without its being contained in tight bags or barrels. The quicklime at the surface becomes "air-slaked," but by so doing it immediately forms a film which protects the bulk of the material.

The rates of hydration of various quicklimes are dependent, first, upon the physical character of the material, finely divided or porous quicklimes being more quickly hydrated because of their greater accessibility to water; second, upon the chemical composition of the quicklimes, high-calcium quicklimes being more quickly hydrated than magnesian or dolomitic quicklimes, and pure limes of either class more quickly hydrated than impure ones; third, upon the temperature of burning of the quicklime, any underburned quicklime having little ability to hydrate, and overburned limes behaving similarly owing to the influence of impurities.

19. Setting and Hardening. The setting of lime and lime mortar is a chemical process involving essentially only the evaporation of the large excess of water used in forming the lime paste, followed by the gradual replacement of the water of the hydroxide by carbon dioxide in the atmosphere, causing the lime hydrate to revert to the original calcium carbonate. Dry carbon dioxide will not react with dry hydrated lime, and it is therefore necessary that excess moisture be present.

20. Plasticity. Sand-carrying Capacity and Yield. The term "plasticity" is commonly used to describe the spreading quality of the material when used in plastering. If it spreads easily and smoothly, it is plastic; if it sticks or drags under the trowel, or cracks, curls up, and drops behind the trowel, it is non-plastic or "short." Magnesian limes produce mortars that work smoothly under the trowel while high calcium mortars are apt to be sticky and work short.

Practically all lime used structurally is made up in the form of a mortar by the addition of sand to lime paste. This circumstance is due not simply to the fact that sand is cheaper than lime, but also that the great shrinkage which accompanies the setting and hardening of lime putty can thus be diminished and the consequent cracking be prevented. The extreme stickiness of some high-calcium limes is also counteracted by the sand.

It is absolutely necessary to mix the lime with from two to four parts of sand to one of lime putty, and it becomes highly important that the "sand-carrying capacity" of the lime be properly established. If too little sand be used, excessive shrinkage will cause a weakening of bond between the plaster or mortar and the masonry materials or plastered surface, and when the bond is mechanically increased, as in the case of plaster spread upon lath, the openings between which provide a key for the mortar, shrinkage cracks inevitably appear. On the other hand, too much sand produces a non-plastic and weak mortar.

The sand-carrying capacity of a lime is expressed by the number of parts of sand which may be added to the lime without rendering the mortar too stiff to work well under the trowel. No fixed standard of sand-carrying capacity has been established. Common experience has shown, however, that pure high-calcium limes excel in sand-carrying capacity, magnesian limes will carry less sand, and dolomitic limes carry least of all.

The volume of paste of a definite consistency which a given amount of lime will yield when slaked is a matter of great practical importance, since the amount of lime required to produce a given quantity of plaster or mortar is estimated therefrom. If a fat lime and a lean lime are slaked with equal proportions of water under the same conditions, the fat lime will produce a thick paste when the lean lime yields a thin milk. The fat lime is said to show the greatest "yield." The yield of a lime can only be expressed by the volume of paste of a stated consistency produced per unit weight of dry quicklime. Pure high-calcium limes yield the largest volume of paste per unit of weight, impure high-calcium and magnesian limes expand less upon being slaked and therefore show a lower yield, and dolomitic limes produce the smallest volume of paste of any class of quicklime.

21. Waste. The determination of the proportion of a 5-pound sample of quicklime made into a paste, which after standing 24 hours cannot be washed through a 20-mesh sieve by a gentle stream of water, serves as a check upon the proper carrying out of the various steps in the manufacturing process.

The material which cannot be washed through the sieve consists of lumps of foreign material which did not disintegrate when the lime was slaked. These lumps impair the working qualities of plaster, and, if they consist of overburned lime, they are apt to become hydrated and expand after the plaster sets, thus causing the "popping" or "pitting" which not infrequently disfigures the surface of plastered walls.

The specifications of the American Society for Testing Materials permit a maximum waste of 3 per cent for selected quicklime, and 5 per cent for run-of-kiln quicklime.

22. Hardness, Time of Setting, and Shrinkage. The hardness of lime mortar, meaning by the term "hardness" resistance to impact and abrasion, has an important bearing upon the suitability of the material for use in wall plasters. No method of testing the hardness of lime mortars has been standardized. Comparative tests made upon various classes of limes, as well as the common experience of builders, have shown, however, that dolomitic limes produce the hardest mortars, magnesian limes are less hard, and high-calcium limes least hard.

The time of setting of limes and mortars is most important in connection with the use of the material in plastering operations. Lime is naturally slow setting, which circumstance causes the loss of considerable time between the application of the different coats. The slow-setting properties of lime, as much as any other one characteristic, have been responsible for the increasing use of quick-setting gypsum plasters.

The humidity and the amount of CO_2 in the atmosphere influence the rate of setting of lime, drying the air and charging it with carbon dioxide, greatly accelerating the setting process.

No experimental method of determining the setting has been standardized. It is a fact well understood by practical masons, however, that magnesian limes are slower setting than high-calcium limes, and the dolomitic limes set still more slowly.

The decrease in volume or "shrinkage" of lime putty which accompanies the process of setting and hardening is directly accounted for by the volume of water lost, the net decrease in volume being slightly affected by an expansion entailed by the gain in carbon dioxide. It is the universal practice to largely overcome the contraction and consequent cracking of mortars and plasters by the addition of several parts of sand to one of lime paste. The only exception to this rule is the fact that neat lime putty is sometimes used as a thin "skim" coat on plastered walls. In this case fine hair cracks do occur, but they penetrate to so slight a depth that they do not open up appreciably.

The amount of shrinkage shown by limes is not closely related to chemical composition, but all magnesian and dolomitic limes shrink less than do high-calcium limes. This circumstance constitutes one reason for preferring the former class of limes for the relatively rich mixtures used for the finish coat on plastered walls.

23. Tensile and Compressive Strength of Lime Mortars. The physical properties of lime mortar vary with the chemical composition of the lime, the amount and character of the sand, the amount of water used and the conditions under which the mortar sets. The very wide variation in the data obtained from tests makes it impossible to present many definite statements with regard to either the tensile or compressive strength.

Tensile Strength. Magnesian limes make stronger mortar than calcium limes. Fine sand makes stronger mortar than coarse sand.

RESULTS OF TENSILE TESTS OF LIME-MORTAR BRIQUETTES MADE AT IOWA STATE COLLEGE

Proportions, Lime : Sand.	Per cent water.	Average Strength of 10 Briquettes in Lb. per Sq. In.									
		Age 3 months.					Age 6 months.				
		Calcium limes.		Magnesian limes.			Calcium limes.		Magnesian limes.		
		Mason City.	Springfield.	Eagle Point.	Mason City.	Maquoketa.	Mason City.	Springfield.	Eagle Point.	Mason City.	Maquoketa.
1 : 1	100	65	96	111	78	128	63	109	154	159	184
1 : 2		76	94	100	92	130	68	97	113	137	167
1 : 3		55	68	90	86	130	53	73	94	119	154
1 : 1	200	45	61	98	54	105	47	62	113	75	153
1 : 2		51	55	90	81	105	53	57	88	98	125
1 : 3		50	55	101	81	100	54	48	104	91	108
1 : 1	300	43	41	120	75	101	42	45	140	96	123
1 : 2		41	45	112	77	86	41	45	114	91	113
1 : 3		46	53	87	70	82	48	51	99	88	96

Compressive Strength. The crushing strength of lime mortar is influenced by the same factors as the tensile strength and in addition the crushing strength also varies with the size of specimen used.

THE VARIATION IN THE COMPRESSIVE STRENGTH OF LIME MORTARS

Tests by Emley & Young

(a) Amount of Sand.			(b) Size of Grains.		
Sand, parts.	Compressive strength, lbs. per sq. in.		Size of sand grains between meshes No.	Compressive strength, lbs. per sq. in.	
	High calcium.	Dolomitic.		High calcium.	Dolomitic.
½	273	372	10–20	98	166
1	151	267	20–30	118	214
2	116	217	30–40	138	312
3	112	202	40–60	186	335
4	116	203	60–80	260	444

Magnesian limes make stronger mortar than calcium limes and fine sand makes stronger mortar than coarse sand.

24. Relative Applicability of Various Limes to Special Uses. High-calcium, magnesium, and dolomitic limes each possess certain special advantages as building materials. Strong preferences exist among plasterers and masons, but these preferences are not always well founded and are not the same in different sections of the country. In the following enumeration of the principal structural uses of limes an effort has been made to indicate the special reasons why one class of lime may be superior to another for the purpose indicated. The limitations of each lime cannot be defined by hard-and-fast rules, however, and divergence from the practices noted will doubtless be frequently encountered on construction work.

Plasters. The plasterer has usually a preference for magnesian or even dolomitic limes. This is due to the fact that these limes work more smoothly under the trowel than do high-calcium limes, and also that the more slow setting properties of these limes make it possible to spread a larger surface in one operation before stopping to complete the surface treatment. Another advantage of magnesian and dolomitic limes is the lessened danger of the development of "lime-pops" caused by the late hydration of small particles of lime. The increased hardness of the wall surface secured with dolomitic limes is also usually considered an advantage.

One possible additional reason for the preference felt by the plasterer for magnesian or dolomitic limes is the fact that he is usually given a richer mortar than would be the case if high-calcium lime were used. This is due to the fact that magnesian limes will not carry as much sand as high-calcium limes.

Mortar for Ordinary Brick Masonry. The bricklayer usually prefers the magnesian or dolomitic lime mortar. Its slow setting properties and greater plasticity make it possible for him to lay a greater number of bricks in one operation.

Mortar for Face Brick. Dolomitic lime is invariably preferred for laying dry-pressed or face brick. This class of bricks is commonly laid with joints not exceeding $\frac{1}{8}$ inch in thickness, and it is absolutely necessary that the mortar be very plastic and very slow setting in order that such thin joints may be secured, and the bricks at the same time be accurately placed in proper alignment.

Mortar for Stone Masonry. High-calcium lime mortars are usually preferred by the stone mason because of their more quickly setting properties, which constitute a distinct advantage. They become stiff enough to carry the load put upon them without deformation in a very short time, thus facilitating the proper setting of heavy stones.

CHAPTER III

HYDRATED LIME

25. Definition. Hydrated lime is a dry flocculent powder resulting from the hydration, at the place of manufacture, of ordinary quicklime.

Hydrated lime is commonly divided into four classes: *High calcium; calcium; magnesian; high magnesian.* The chemical composition is practically the same as for the corresponding classes of ordinary lime.

26. Process of Manufacture. Three stages of manufacture characterize the preparation of hydrated lime.

The lump quicklime is crushed to a fairly small size.

The crushed material is thoroughly mixed with a sufficient quantity of water.

The slaked lime is, by air separation, screening, or otherwise separated from lumps of unhydrated lime and impurities, or the entire mass must be finely pulverized.

Crushing. The degree of crushing employed at various hydrated lime plants varies greatly. In some plants the quicklime is crushed to a 1-inch size; in others the quicklime is crushed to a size of ½ inch or under. A few plants, after crushing the quicklime, pulverize it so that the greater portion will pass a 50-mesh sieve.

Mixing with Water. The two methods extensively used for hydrating quicklime are the batch process, using a machine of which the Clyde hydrator is typical, and the continuous process, in which a machine of which the Kritzer hydrator is typical is used. Either process may give entire satisfaction providing only that the plant operation is properly supervised and the character of the product kept under strict chemical control.

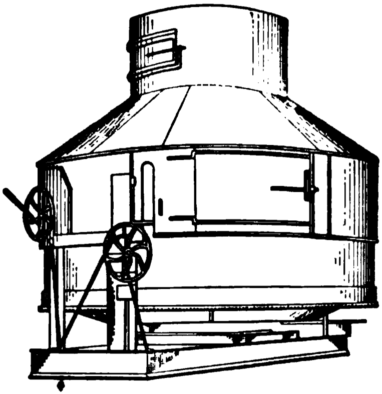
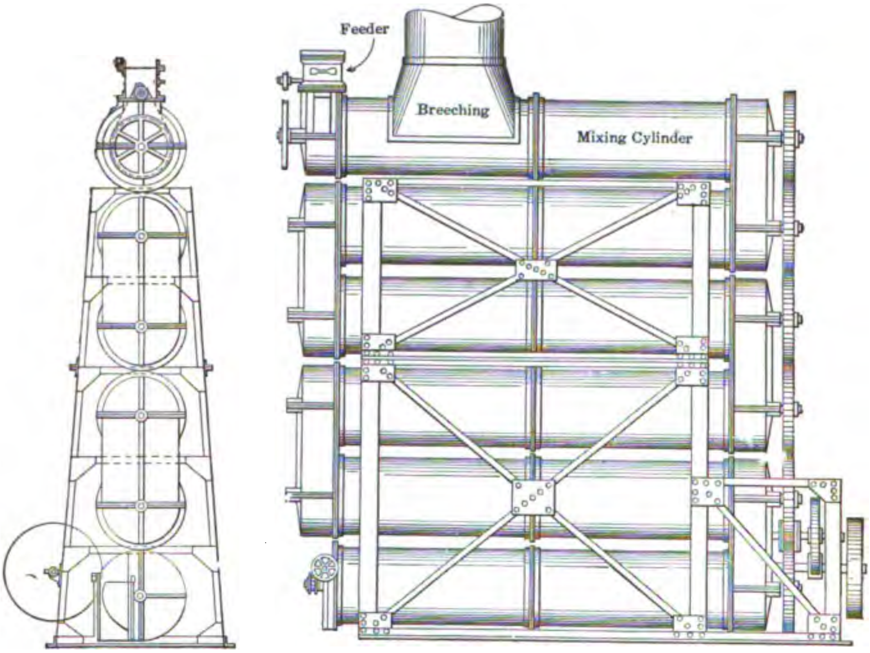


FIG. 8. — Clyde Hydrator.

The Clyde batch process hydrator (Fig. 8), is a machine in which a quantity of quicklime (usually 1 ton) is placed, and the proper quantity of water added by means of a spray. The machine itself consists of a revolving pan provided with plows, arranged in a horizontal spiral, which stir up and mix the water and lime. The water is

weighed and added in a predetermined amount. The hydrated lime is scraped from the pan through an opening in the center into a hopper below the hydrator.

The Kritzer continuous process hydrator (Fig. 9), consists of a number of cylinders, arranged one above the other, which are provided with screw-conveyors revolving around a central shaft. The quicklime is fed into the upper cylinder in a continuous stream and here water is sprayed upon it, the amount being regulated by valves. The moist lime is gradually worked by the conveyors through the upper cylinder into the lower ones, and by the time it is discharged from the lowest cylinder it is entirely hydrated.



End Elevation. Side Elevation.

FIG. 9. — The Kritzer Continuous Hydrator.

Removal of Lumps of Unhydrated Material. Owing to the increase in volume which accompanies slaking, the lumps of lime fall into powder during the process. Any impurities in the lime will not slake, and will remain with any imperfectly hydrated lime as lumps which can be removed from the finished product by screening or air separation.

The form of screen usually employed consists of a wire netting stretched on an inclined frame which is mechanically agitated as the material traverses its length. The usual size is from 35 to 50 meshes per linear inch. The whole structure must be enclosed to keep in the dust.

Air separation systems usually involve the use of a Raymond impact mill or similar device in which the hydrate is subjected to the beating action of rapidly revolving blades. The material encounters a current of air by which the fine material is carried off in suspension, while the larger particles settle out. The fine material is subsequently deposited in a chamber provided for the purpose in the air duct, the precipitation being effected by the reduction in velocity of the air current. The air circuit is a closed one, the same air being used over again, and it is therefore a dust-proof device. A regulation of the size of the particles is easily attained by varying the velocity of the air current through the speed control of the fan.

27. Properties and Uses. Hydrated lime and ordinary lime which has been properly slaked on the work are the same material, and therefore should have identical physical properties. Experience has shown, however, that stronger and more quickly setting mortars, which shrink less upon setting and hardening, are derived from hydrated limes than from ordinary quicklime. On the other hand, mortars prepared from hydrates are vastly inferior to those prepared from quicklimes from the standpoint of plasticity, sand-carrying capacity and yield, unless the hydrated lime paste is allowed a period of seasoning before being used.

The strength of hydrated lime mortars, both in tension and compression, is somewhat higher than that of the corresponding quicklime mortars. This superiority is particularly noticeable in the case of high calcium limes. The only physical tests for hydrated lime that have been standardized are for fineness and constancy of volume.

Fineness (A. S. T. M. standard): "A 100-gram sample shall leave, by weight, a residue of not more than 5 per cent on a standard 100-mesh sieve, and not more than 0.5 per cent on a standard 30-mesh sieve."

Constancy of volume (A. S. T. M. standard): "Equal parts of hydrated lime and volume constant Portland cement shall be thoroughly mixed together and gaged to a paste. Only sufficient water shall be used to make the mixture workable. From this paste a pat about 3 inches in diameter and ½ inch thick at the center, tapering to a thin edge, shall be made on a clean glass plate. This pat shall be allowed to harden 24 hours in moist air and shall be without popping, checking, warping or disintegrating after 5 hours' exposure to steam above boiling water in a closely closed vessel."

28. Hydrated Lime vs. Quicklime. The superiority of hydrated lime over the ordinary lump lime from the standpoint of the mortar strength developed has been indicated. The advantage accruing from the use of a material which need only be mixed with water, instead of being slaked upon the work with the attendant danger of burning or incomplete hydration, has also been noted. There remain certain advantages and disadvantages to be derived from the use of the commercial hydrate which will be considered briefly.

Hydrated lime can be more conveniently handled than lump lime because of its powdered condition, and can safely be stored or shipped by rail or water in cloth or paper bags or even in bulk. On the other hand lump lime deteriorates rapidly in storage or transportation, through air-slaking, is considered an unsafe commodity to carry by water, and wherever kept always constitutes a fire hazard.

One property of hydrated lime which often constitutes an advantage on construction work is the fact that it is ready to be immediately incorporated with sand and water to form mortar, whereas ordinary lime must be allowed to season for from one day to several weeks after being slaked, thus causing delay.

The fact that hydrated lime is a physically dry material is an advantage in mixing mortars. The dry hydrate can be mixed with sand much more easily than a lime paste or putty, and a more homogeneous mixture is obtained before the excess water is added to make a plastic mortar.

On the other hand, mortars prepared from hydrated lime are very "short" and non-plastic, the volume of lime paste derived is small, as compared with that obtainable from quicklimes, and the sand-carrying capacity is low. The lack of plasticity of hydrated lime mortars is alone sufficient to condemn the material from the standpoint of the practical mason and plasterer. Some hydrates are, indeed, so lacking in colloidal properties that they are absolutely gritty. As a result there is almost no market for hydrated lime as a plastering or finishing lime, with the exception of certain hydrates of special character which are produced to a limited extent.

The greatest value of hydrated lime as a structural material is in Portland cement mortars and concretes. It is also used in combination with gypsum plaster.

29. Special High Alumina Hydrated Lime. The unsatisfactory properties of hydrated lime as a plastering material on account of the non-plastic, poor working mortars formed, and the slowness with which plastered walls dry out and harden, has led to many attempts to so modify the characteristics of the material as to correct these defects.

These efforts have been far from uniformly successful, but, in at least one instance, a material has been produced whose performances have made a very favorable impression upon the architect, builders, and artisans, and the material has come to be a fairly well-known article of commerce.

This product, marketed under the trade name "Alca Lime," is made by the incorporation with selected hydrated lime of about 15 per cent of a patented calcium aluminate compound which is derived as a slag from blast furnaces. This compound is not a normal blast furnace slag, but comes from a furnace whose charge is so regulated that a slag high in alumina and relatively low in silica is produced. Its composition is about 25 to 35 per cent alumina, 20 per cent silica, and 35 to 40 per cent lime and magnesia. The slag is granulated by running the molten material into water or by causing it to encounter a jet of steam or water, and the material is subsequently ground to such a degree of fineness that not more than about 25 per cent will be retained on a 200-mesh sieve.

The lime manufacturer secures this material in a pulverized condition and mixes it with his finished hydrated lime. An ordinary mixer is often used, but greater uniformity is obtained if the two materials are passed together through a mill designed for fine pulverization of cement and other similar materials.

Alca lime comes upon the work ready to be mixed with sand and water and be used almost immediately. Best results are obtained if the sand and lime are first mixed dry, then combined with about 16 per cent of water, thoroughly mixed, and allowed to stand for not less than one hour before being used.

CHAPTER IV

HYDRAULIC LIME AND GRAPPIER CEMENTS

HYDRAULIC CEMENTING MATERIALS IN GENERAL

30. Introductory. The cementing materials previously considered have all belonged to the class of non-hydraulic cementing materials; all have been simple both in composition and in chemical action. The hydraulic cementing materials, however, comprize a class of products of very complex and somewhat variable composition and constitution, whose physical characteristics are not definitely fixed, and whose actual constitution is imperfectly understood.

These materials all possess, in common, one property known as "hydraulicity," i.e., the ability to set and harden under water. In composition they agree to the extent that they all consist essentially of lime, silica, and alumina, or of lime and magnesia, silica, and alumina and iron oxide. The hydraulic cementing materials include hydraulic limes, grappier cements, puzzolan cements, natural cements, and Portland cements.

31. Classification of Cementing Materials.

Common Lime. Lime made by burning relatively pure limestone at a very low temperature, the product being one which slakes when mixed with water and which possesses no hydraulic properties.

Hydraulic Limes. Limes made by burning slightly argillaceous limestones at a low temperature, the product being one which will slake slowly but which at the same time possesses feebly hydraulic properties.

Natural Cements. Cements made by burning distinctly argillaceous limestones at a comparatively high temperature, the product being one which will not slake, but which when ground possesses hydraulic properties.

Portland Cement. Cement made by burning an artificial mixture of argillaceous and calcareous materials at the temperature of incipient vitrification, the product being one which will not slake but which when ground possesses marked hydraulic properties.

Puzzolan or Slag Cements. Cements made by incorporating slaked lime with granulated blast furnace slag or a natural puzzolanic material such as volcanic ash without subsequent burning, the product being one which will not slake, but which when ground possesses hydraulic properties.

HYDRAULIC LIMES

32. Definition and Classification. The hydraulic limes include all those cementing materials, made by burning siliceous or argillaceous limestones whose clinker after calcination contains a sufficient percentage of lime silicate to give hydraulic properties to the product, but which at the same time contain normally so much free lime that the mass of clinker will slake on the addition of water.

The hydraulic limes therefore occupy an intermediate position between the common limes and the more complex cements.

33. Hydraulic Limestones. The ideal hydraulic limestone rock should have such a composition that, after all the silica has combined with lime during calcination, sufficient free lime remains to disintegrate the kiln product by the expansive force set up when it is slaked.

The limestones used in the manufacture of hydraulic limes usually contain from 40 to 50 per cent of lime and magnesia, 4 to 17 per cent of silica, and usually not more than 4 per cent of alumina and iron oxide.

34. Calcination. The burning of hydraulic limes is accomplished in continuous kilns. The operations involved in the process of calcination are practically identical for common lime and for hydraulic lime except that the temperature required is somewhat higher in the latter case.

35. Slaking and Subsequent Treatment. The theory of slaking of hydraulic lime differs from the slaking of common quicklime in no respect except that in the former case the quicklime, which will slake, is intimately associated in lumps with lime silicate, under-burned limestone, and some aluminate and ferrites, none of which can be slaked. The expansion of the quicklime in slaking, however, breaks up the entire mass into a fine powder which will consist principally of lime silicate together with one-fourth to one-third as much hydrated lime.

The slaking of hydraulic lime was at one time done by the purchaser upon the work. It is now, however, practically the universal practice to slake the lime at the place of manufacture. The lump lime as drawn from the kiln is spread out in thin layers and sprinkled lightly with water. It is then shoveled into heaps or bins where it is allowed to remain for about ten days till the slaking is completed. In order that the product may be a fine, dry powder, the slaking must be done carefully and with just the right amount of water.

A certain proportion of the kiln product either does not contain sufficient lime or is not sufficiently burned to be slaked upon the addition of water, and consequently remains as hard lumps called "grappiers." The slaked material is passed over screens of about 50 meshes per linear inch, which reject all of the larger particles. This rejected material is valuable or not according to whether it consists principally of lumps of lime silicate on the one hand or unburned limestone on the other hand. As a rule all of the grappiers are finely ground under millstones and a certain proportion is added to the lime, thereby increasing its hydraulicity in proportion to the amount of lime silicate present. The ground grappiers are also separately marketed as a special cement known as *grappier cement.*

36. Physical Properties. The physical properties of hydraulic limes are indicated by the following data from the work of Tetmajer.

TESTS OF HYDRAULIC LIMES

TENSION, AIR STORAGE

	1 : 3						Neat.					
	7 days.	28 days.	84 days.	210 days.	1 year.	2 years.	7 days.	28 days.	84 days.	210 days.	1 year.	2 years.
Average	100.7	184.5	211.9	400.2	306.5	287.0	92.4	184.4	307.5	433.8	541.9	553.3
Maximum	236.1	385.5	367.0	526.3	614.4	344.2	123.7	250.3	406.8	493.5	779.4	.....
Minimum	43.7	82.5	76.8	230.4	155.0	183.5	75.4	91.0	79.7	293.0	143.7	.....
No. tests	(8)	(8)	(8)	(3)	(8)	(4)	(6)	(6)	(6)	(5)	(6)	(1)

TENSION, WATER STORAGE

Average	56.8	108.5	210.9	304.3	316.2	325.6	66.0	129.8	235.6	308.6	352.2	460.8
Maximum	95.3	174.9	342.8	465.1	463.7	409.6	108.1	179.2	345.6	421.0	439.5	.....
Minimum	32.7	46.9	102.4	166.4	213.3	268.8	29.9	82.5	153.6	253.6	300.1	.....
No. tests	(16)	(22)	(22)	(17)	(22)	(12)	(8)	(8)	(8)	(7)	(8)	(1)

COMPRESSION, AIR STORAGE

Average	511.0	900.3	1184.7	2409.1	1834.0	1709.6	455.1	1026.2	1884.0	2769.7	2918.3	3213.2
Maximum	981.7	1779.0	2201.5	2903.3	3552.9	2200.5	776.5	1415.2	2580.0	3590.0	4147.4	....
Minimum	196.2	398.3	632.9	1763.4	1016.9	1112.2	190.6	791.2	1103.6	1947.2	1514.7	.....
No. tests	(8)	(8)	(8)	(3)	(8)	(4)	(6)	(6)	(6)	(5)	(6)	(1)

COMPRESSION, WATER STORAGE

Average	342.5	676.9	1189.9	1806.7	1924.9	2116.9	330.5	720.4	1543.1	2579.6	3026.3	4083.4
Maximum	709.7	1109.4	2511.5	3648.5	3625.6	2988.4	634.4	995.0	2508.9	3285.4	3642.6	.....
Minimum	123.7	300.1	587.4	933.0	1110.7	1318.4	146.5	448.0	816.4	1479.3	19995.6	.....
No. tests	(19)	(20)	(22)	(17)	(22)	(12)	(7)	(8)	(8)	(7)	(8)	(1)

37. Hydraulic Limes in Construction. Hydraulic limes were used by engineers for various structural purposes before the advent of the greatly superior natural cements, and now the latter product is almost entirely replaced as an hydraulic cementing material by Portland cement.

Hydraulic limes are not suitable for use on subaqueous construction, in spite of their designation; they are too slow setting to render their use on general construction work convenient and practical, and their comparative weakness makes competition with natural and Portland cement impossible. Their only present value is that of an architectural decorative material rather than a material for engineering construction.

CHAPTER V

PUZZOLAN CEMENTS.* SLAG CEMENTS

PUZZOLAN CEMENTS

38. General. The oldest known hydraulic mortars were undoubtedly made by the incorporation of a volcanic tufa with slaked lime and sand. Thus were produced the cements extensively used by the Romans and other ancient peoples in the construction of many engineering structures, a few of which remain to-day in a remarkable state of preservation.

The activity of the volcanic material depends upon the presence of weakly acid silico-aluminates which combine more or less readily with lime hydrate at atmospheric temperatures.

39. Definition of Puzzolans and Puzzolan Cement. The natural or artificial materials which contain a sufficiently large percentage of available silica to combine with lime hydrate and form a cement possessing hydraulic properties are known as "puzzolans."

Puzzolan cements include all that class of hydraulic cementing materials which are made by the incorporation of natural or artificial puzzolans with hydrated lime without subsequent calcination.

The true puzzolan cement, often called "slag cement," made by incorporating blast-furnace slag with hydrated lime without subsequent burning, must not be confused with the Portland cement, which is made by finely pulverizing the clinker derived by the calcination of an intimate mixture of the same materials.

40. Natural Puzzolanic Materials. All natural puzzolanic materials of any commercial importance as cement materials are of the same general character and have a like geological origin. All are direct products of volcanic action and the commercial puzzolanic materials are invariably derived from deposits of more or less agglomerated volcanic ash.

The natural puzzolanic materials and the principal artificial puzzolanic material, granulated blast-furnace slag, have their origin in practically the same processes. In both cases a more or less finely divided

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* The term "puzzolan," which is commonly applied to this class of cements by American authorities, is a corruption of the name "puzzuolana" which refers to the class of volcanic material first utilized as a hydraulic cementing material at the town of Puzzuoli, near Naples. Continental writers call these cements "puzzuolana" cements.

siliceous material is derived by the sudden cooling and ejection into air or immersion in water of a fused silico-alumious material.

The only natural puzzolanic material of commercial importance as cement materials are "puzzuolana," "trass," "santorin " and "tuff " or "tufa." The latter material has been used in making only one brand of cement, and in that case it is not used in conjunction with lime, but is finely ground and mixed with an equal amount of ordinary Portland cement and the resulting blend subsequently finely pulverized to produce a "tufa-Portland " cement, which is neither a true puzzolan nor a true Portland.

AVERAGE ANALYSES OF NATURAL PUZZOLANIC MATERIALS

	Puzzuolana, Italy.	Puzzuolana, France.	Puzzuolana, Azores.	Trass, Germany.	Santorin.	Average of all puzzolans.
Number of analyses	9	7	3	11	1	31
SiO_2	50.98	41.91	57.78	53.78	66.37	51.08
Al_2O_3	15.55	16.16	15.15	17.38	13.72	16.30
Fe_2O_3	14.41	19.30	10.37	6.89	4.31	11.13
CaO	7.39	6.93	2.84	3.89	2.98	5.46
MgO	1.96	1.37	1.63	1.17	1.29	1.50
K_2O, Na_2O	6.63	5.15	4.52	6.82	7.05	6.21
H_2O	5.09	7.89	7.61	9.22	4.06	7.64

41. Manufacture of Puzzolan Cements from Natural Materials. The preparation of puzzolan cements is a simple mechanical process involving nothing more than the screening, mixing, and grinding of the two constituents employed.

Most deposits of natural puzzolans are subject to great variation in the quality of the material, therefore necessitating careful selection or sorting of the quarry product to exclude inferior material. Screening of the puzzolan is usually necessary in order to exclude undesirable adulterants.

Puzzolanic rock is not usually mixed with hydrated lime at the place of manufacture, but is pulverized and marketed as a material to be incorporated with hydrated lime paste and sand where used in construction work. The proportions of the mixtures used in mortars are not fixed, but the proportion of lime usually amounts to from one-third to one-half the proportion of puzzolan, and the puzzolan cement thus formed may be combined with sand up to about three times the proportion of cement.

42. Properties and Uses of Natural Puzzolan Cements. Puzzolan cements made from natural materials hold so unimportant a place among structural materials that little study of their physical characteristics has been made, and no data has been obtained in any recent investigations.

The tensile and compressive strengths of three puzzolan cements tested by Dr. Boehme are presented by the curves of Fig. 10. All specimens were composed of one part by weight of puzzolan cement to three parts by weight of sand. Similar tests were made on specimens hardened in air and other specimens hardened in water, the strength being determined for each at seven days and at twenty-eight days. In every case the specimens stored in water were found to be stronger than the corresponding air-stored specimens.

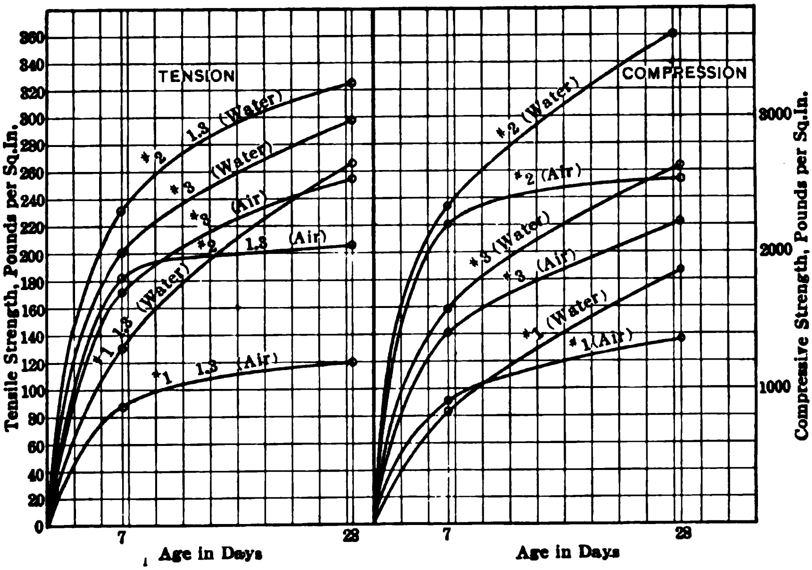

FIG. 10.

SLAG CEMENTS

43. Definition. Slag cement may be defined to be an intimate mechanical mixture of granulated blast-furnace slag of suitable chemical composition, with hydrated lime, the materials having been finely pulverized before, during, or after mixing.

No calcining of the mixture is practiced, and the product is not to be confused with the true Portland cement which is produced by the calcination and subsequent pulverization of a properly proportioned mixture of blast-furnace slag and raw limestone.

44. Blast-furnace Slag. Blast-furnace slags, such as are suitable for use in slag cements, are fusible lime silicates derived as waste products from the operation of blast furnaces in smelting iron from its ores. The slag is formed for the most part by the combination in the furnace of the earthy part of the ore, with lime from limestone which is charged with the ore as a flux. Slags are produced in many metallurgical processes other than the reduction of iron ores. Only the latter process, however, is capable of producing the very basic slag required for cement manufacture.

The required composition of the slag according to American practice is within the following approximate limits: CaO, 48 to 50 per cent; SiO_2, 32 to 35 per cent; Al_2O_3. 12 to 16 per cent MgO, Fe_2O_3 S, etc., 2 to 5 per cent.

Slag, as it comes from the blast furnace if allowed to cool slowly, is a very dense and hard material, and has, moreover, such a chemical constitution that even when pulverized it does not combine energetically with water, nor exhibit more than very feebly hydraulic properties. If the molten slag is cooled very rapidly, however, by the use of cold water, it becomes broken up into small porous particles which can be economically handled by the pulverizing machinery.

Two important chemical effects are also attained by the process of granulating the slag; the slag is rendered more hydraulic, thus providing a stronger cement, and the content of undesirable sulphides always encountered in slags is reduced.

45. Manufacture of Slag Cements. The process of manufacture of slag cements involves the following operations: granulation of the slag, drying the slag sand, preparation of the hydrated lime, proportioning the mixture, mixing and grinding.

The granulation of the slag may be accomplished by a jet of high-pressure steam which the stream of slag encounters as it issues from the furnace. Air jets have also been similarly used, but both of these methods have been generally replaced by an arrangement whereby the stream of slag from the furnace falls into a trough containing a rapidly flowing stream of cold water. This method is a very satisfactory one as it produces a slag sand which is quite porous and friable and has the proper chemical composition. It is charged with much moisture, however, and must be dried before being mixed with the hydrated lime.

The slag as it comes from the bins into which it has been discharged by the granulating device, carries from 15 to 45 per cent of water. The removal of this water is accomplished through the agency of heat in either a rotary cylinder or in a vertical shaft dryer, into which the material is introduced at the top and dried by ascending hot furnace gases as it traverses a series of inclined baffle plates toward the base. Rotary dryers are used exclusively in the United States.

The hydrated lime used in slag cement in American practice is a very pure high-calcium lime.

The proportioning of the mixture of slag and lime is usually done according to some established standard found by experiment at each plant to produce the most satisfactory cement with the materials in hand. The standard proportions of slag and lime vary at different plants from as low as 25 pounds of lime, to as high as 45 pounds of lime, for 100 pounds of slag sand.

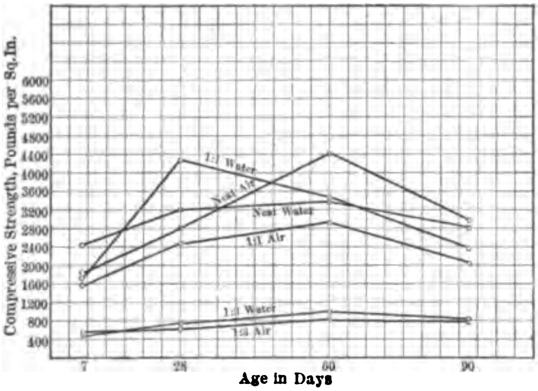

Fig. 11. — Tensile Strength of Slag Cements.

The best method of grinding and mixing the slag and lime probably consists in grinding the slag sand in a ball mill or other type of grinder, adding the hydrated lime, and accomplishing the mixing and final pulverization of the mixture simultaneously in a tube mill or other type of cement-finishing mill.

Slag cements are normally more slowly setting than Portland cements and on this account are often treated with some class of puzzolanic material which will hasten the setting. Materials so used are burned clay, high-alumina slags, certain active forms of silica, and in the patented "Whiting" process, caustic soda, sodium chloride or potash. The amount of such materials added as an accelerator does not usually exceed about 3 per cent by weight, and unless the material is to qualify under the usual specifications for Portland cement no accelerator should be necessary. Any addition to the cement made for the purpose of regulating the set must be made prior to final pulverization.

46. Properties and Uses of Slag Cements. The usual range of composition of American slag cements is indicated by the following summary.

SiO_2.	$Al_2O_3+Fe_2O_3+FeO$.	CaO.	MgO.	S.	CO_2+H_2O.
27.2–31.0	11.1–14.2	50.3–51.8	1.4–3.4	0.15–1.42	2.6–5.3

The specific gravity of slag cements usually ranges between 2.7 and 2.85, which fact affords a means of distinguishing slag cements from natural cements, which rarely fall below 2.9, and Portland cements, which must under the standard specifications be not less than 3.1.

The fineness of grinding practiced in making slag cements is about equal to that commonly attained in grinding Portland cements.

The strength of American slag cements is shown by Figs. 11 and 12, which are based upon tests made by Professor W. K. Hatt at Purdue University.

The use of slag cement is limited to unimportant structures or to work requiring large masses of concrete masonry where weight and bulk are more important than great strength. It is seldom used on structures above the foundations, and never used on comparatively light reinforced concrete construction.

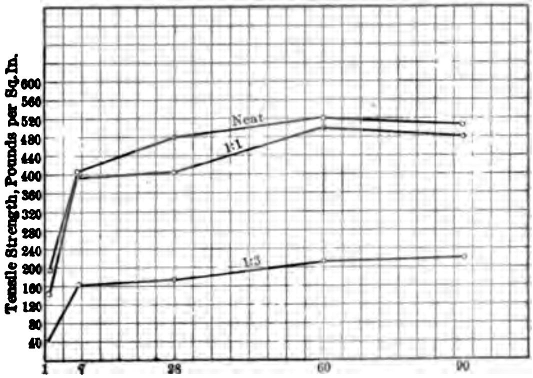

FIG. 12. — Compressive Strength of Slag Cements.

CHAPTER VI

NATURAL CEMENTS

47. Definition. Natural cement may be defined as the finely pulverized product resulting from the calcination of a natural argillaceous limestone at a temperature sufficient to drive off the carbon dioxide gas and also decompose the clay and effect the formation of aluminates, ferrites and silicates.

The distinctions between natural and Portland cements may be summarized as follows:

	Natural cements.	Portland cement.
Raw material	Natural argillo-calcareous rock	Artificial argillo-calcareous mixture
Calcination Temperature	Low	Relatively high
Chemical Composition	Variable, not under control	Controllable within narrow limits
Color	Usually yellow to brown	Usually blue-gray
Specific gravity	2.7 to 3.1	3.1 to 3.2
Rate of setting	Normally rapid	Relatively slow
Strength	Low	Relatively high

48. Natural Cement as a Structural Material. Natural cement is used to a rather limited extent as the cementing ingredient of concretes and, in combination with sand, as a mortar for laying brick and stone masonry. In all of these applications it comes into direct competition with Portland cement and suffers by comparison.

MANUFACTURE OF NATURAL CEMENTS

49. Natural Cement Rocks. Natural cements are invariably made by the calcination of a natural clayey limestone carrying from 13 to 35 per cent of clayey material, 10 to 20 per cent of the clayey material being silica, and the balance alumina and iron oxide. The hydraulic properties of the cement are entirely due to the presence of this clayey material. The calcium carbonate of the limestone may be replaced to a considerable degree by magnesium carbonate, resulting in the replacement of lime by magnesia to a corresponding degree in the manufactured product.

Argillaceous limestones of the composition required for the manufacture of natural cement are widely distributed. There are, however, only comparatively few districts where the natural cement industry has ever become commercially successful. This fact is due to the necessity for certain commercial advantages dependent upon the character and location of the quarries. Among these requisites may be mentioned a rock of at least fairly uniform composition, a favorable location of the rock beds for cheap extraction of the cement rock, cheap fuel and good transportation facilities.

50. Theory of Calcination. The rock as it is charged into the kiln consists essentially of lime and magnesium carbonate with a more or less definite percentage of clayey matter. The chemical changes that take place during calcination may be briefly mentioned as follows:

Water mechanically held by the rock is first driven off; at a temperature of about 800° C. (1472° F.) magnesium carbonate is dissociated, the carbon dioxide being driven off; at a temperature of about 900° C. (1652° F.) the lime carbonate is similarly dissociated; at a temperature of 900° (1652° F.) to 1000° C. (1832° F.) the clay is decomposed and the formation of aluminates and ferrites of lime and magnesia is effected; lastly, at a temperature of about 1300° C. (2372° F.), silicates of lime and magnesia are formed.

51. Practice of Calcination. *The Kiln.* The type of kiln most used in the United States' natural cement industry is of the continuous vertical mixed feed type, the rock and fuel being either mixed or charged in alternate layers.

The Campbell kiln (Fig. 13) consists of an inner cylindrical kiln of masonry, lined with firebrick and enclosed by a sheet-steel cylinder separated from the masonry by a thick layer of clay. The interior diameter of the kiln is 11 feet from a point about 9 feet above the pot to a point about 8 feet below the top. The kiln gradually narrows below this zone to a diameter of about 6 feet 7 inches at the top of the pot, and above this zone to a diameter of about 9 feet. The height of the kiln above the top of the pot is about 28 feet. The pot is an open grating of iron in the form of an inverted cone about 3 feet 6 inches in diameter at the bottom where the calcined material is withdrawn. The capacity of such a kiln is from 125 to 150 barrels (265 pounds) per day. Other types of kiln in common use in America differ from the Campbell kiln in only one essential detail — the replacement of the iron kiln-pot by a masonry pot. The Campbell is somewhat more economical to build and more convenient in operation.

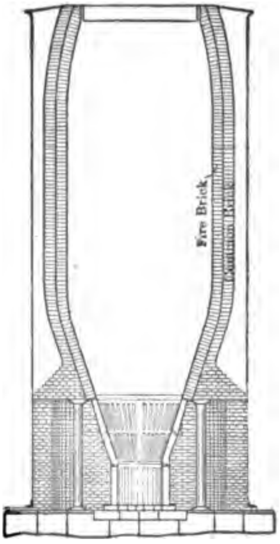

FIG. 13. — Campbell Kiln for Natural Cement.

The Fuel. The fuel used in natural-cement burning is usually bituminous coal. The fuel consumption varies greatly, because differences in composition of the rock cause variation in the required calcination temperature.

52. The Clinker. The output of a natural-cement kiln includes three classes of material: hard-burned clinker, soft porous moderately burned material, and practically unburned material. The recognition of the presence of these three classes of material is necessary, because with some rocks the best cement is derived from the soft moderately burned material, and in many cases the best cement is a mixture of both materials. Unburned material is valueless.

With cement rock high in lime and magnesia the possible range of temperature for proper calcination is shortened, with consequent greater possibility of high percentages of free lime. The presence of this free lime may be neutralized by some method of slaking. This is commonly done by sprinkling or steaming the unground clinker. This expedient decreases grinding costs, since the slaking of the lime will disintegrate the clinker to some extent.

53. Grinding. The clinker is crushed in some form of crusher and then finished in some one of the various types of grinders and pulverizers used in Portland cement manufacture.

PROPERTIES OF NATURAL CEMENTS

54. Chemical Composition. The average composition of various natural cements is indicated by the following summary.

SiO_2.	Al_2O_3.	Fe_2O_3.	CaO.	MgO.
22.3–29.0%	5.2–8.8%	1.4–3.2%	31.0–57.6%	1.4–21.5%

It will be apparent that the composition of natural cements is extremely variable. The wide variations in composition are accompanied by great differences in mechanical properties.

55. Specific Gravity. The specific gravity of natural cements is slightly below that of Portland cements, the average being about 2.95.

56. Time of Setting. Natural cements normally are quick setting as compared with Portland cement. The standard specifications prescribe that the initial set shall take place in not less than ten minutes, and hard set in not less than thirty minutes or more than three hours.

The addition of gypsum or plaster of Paris has a very marked effect in retarding the set of natural cements, the degree of retardation with a given percentage of gypsum being largely dependent upon the chemical composition of the particular cement.

57. Fineness. The general practice is to meet and even exceed the requirements of the standard specifications of the Am. Soc. for Testing Materials which permit a maximum residue of 30 per cent on the 200-mesh sieve and 10 per cent on the 100-mesh sieve.

58. Tensile Strength. In tensile strength natural cements vary quite as much as they do in other physical properties. This variation is found not only in comparing cements from different localities, but even in comparing samples taken at different times from the output of any one locality. The only general statement that may be made concerning their strength is that natural cements rarely show more than half the tensile strength of Portland cement of the same age. This is true not only of neat cement, but also of mortars of all proportions.

The standard specifications of the Am. Soc. for Testing Materials fix the following minimum requirements for tensile strength:

	Neat cement, lbs. per sq. in.	1 : 3 standard mortar. Lbs. per sq. in.
24 hrs. in moist air	75	....
24 hrs. in moist air, 6 days in water	150	50
24 hrs. in moist air, 27 days in water	250	125

It is further stipulated that the cement shall show no retrogression in strength within the periods specified.

59. Compressive Strength. The above remarks concerning the variability of tensile strength of natural cements apply equally well to compressive strength. In general it may be stated that the compressive strength of natural cement, neat or mortars, rarely exceeds one-third that of Portland cement in similar mixtures.

60. Where Natural Cement May be Used. When economy is effected thereby, natural cement may be substituted for Portland cement in mortars and concrete for dry heavy foundations where the stresses encountered will never be high, for backing or filling in massive masonry in dry situations where weight and mass are more essential than strength, for laying brick and stone masonry subjected only to light loads and not exposed, for pavement foundations, for sidewalks, etc. It should not be used in exposed situations, should not be placed under water, it is unsuited for use in marine construction, and should not be used in building construction above the foundation.

SECTION 2

CHAPTER I

PORTLAND CEMENT

1. Historical. In 1824, Joseph Aspdin, a brick mason of Leeds, England, was granted a patent on a method of manufacture of a cement for which he proposed the name "Portland cement," because of a real or fancied resemblance of the concrete made with it to the natural limestone extensively quarried for building purposes at Portland, England. He proposed to make his cement from limestone combined with clay, by burning the mixture and subsequently grinding the product. Aspdin is usually given the credit for the invention of Portland cement, although the specifications in his patent failed to state either the relative proportions of clayey and calcareous material necessary or the required degree of calcination of the mixture.

In the United States the cement industry began with the discovery in 1818 of a natural cement rock in Madison County, N. Y., by Canvass White, an engineer on the construction of the Erie canal. The natural cement made and patented by White was used in large quantities in the construction of the canal. Within a few years after the discovery of natural cement rock in Madison Co., N. Y., other deposits were found, and the manufacture of natural cement began in many other places.

The first Portland cement manufactured in the United States was made at Coplay, Pa., in 1875, by David O. Saylor, by calcining at a high temperature a mixture of argillaceous limestone rock with a comparatively pure limestone. During the next five years several Portland cement plants were put in operation in the United States. Between the years 1880 and 1890 the Portland cement industry grew slowly, but it was not until 1895, with the introduction of coal burning in the rotary kiln, that there began the phenomenally rapid growth which has since characterized the industry.

2. Definition of Portland Cement. The term "Portland cement" is applied to the finely pulverized product resulting from the calcination to incipient fusion of an intimate artificial mixture of argillaceous and calcareous materials, this product to contain not less than 1.7 parts by weight of lime to 1 part by weight of silica + alumina + ferric oxide, not more than 4 per cent of magnesia, nor more than 1.75 per cent of anhydrous sulphuric acid, and to which no addition greater than 3 per cent shall have been made subsequent to calcination.

The raw materials must be mixed in quite exact proportions obtainable only in an artificial way under chemical control. Burning to incipient fusion (sintering) insures the high density so essential to Portland cement. The provision allowing a maximum magnesia content of 4 per cent assumes that this magnesia content is taken into account in adding the lime. An excess of magnesia tends to cause unsoundness of cement. The allowance of a maximum sulphuric acid content of 1.75 per cent is necessary because of the unavoidable presence of sulphurous compounds in the raw material and in the fuel. In addition, sulphur compounds are necessarily introduced by the addition of gypsum or plaster of Paris to regulate the time of setting. The provision limiting the additions made subsequent to calcination to 3 per cent is designed primarily to prevent the possibility of additions made solely for the purpose of increasing the weight.

3. Portland Cement as a Structural Material. Portland cement is by far the most important of all masonry materials used in modern engineering construction. As monolithic concrete it is used in all types of massive masonry, such as foundations, footings, piers, abutments, dams, retaining walls, pavements, roadways, etc. When reinforced with steel it is used for framework, walls, floors, and roofs of buildings, for bridges, for tunnels, subways, conduits, and innumerable other purposes. In combination with sand and lime it is used as mortar for laying brick or stone, and as a plaster or stucco it is applied to either exterior or interior walls upon a base of terra cotta, brick or metal lath.

In general cement holds rank as a structural material second only to steel. An enormous amount of timber is used structurally but only a comparatively small amount is used on important permanent work whose features possess interest from the strictly engineering point of view.

One great difference exists, in the conditions under which cement is used as compared with steel. Steel is delivered upon the work as a finished material, manufactured under standardized conditions, every step in the metallurgical processes involved in its production, and the mechanical operations of its fabrication having been most carefully supervised. Upon the work the fabricated units are assembled, by workmen specially trained in doing this one class of work.

Cement, on the other hand, although manufactured under well-standardized conditions, is received upon the work as one ingredient only of a structural material, which is built in place. The materials which are combined with it to form concrete or mortar, i.e., sand and crushed stone or gravel, are often used without careful examination or selection, and the mixing and the deposition of the material in place sometimes does not receive proper supervision.

PORTLAND CEMENT MANUFACTURE

4. Raw Materials. The essential constituents of Portland cement are lime, silica, and alumina. With the exception of lime these substances are found free in nature, but not, however, in a form suitable for use in cement manufacture. Lime is always used in the form of a carbonate, and silica and alumina in the form of clay, shale, or slate.

The following classification of the raw materials may be made:

Calcareous. ($CaCO_3$ over 75%)	Argillo-calcareous. ($CaCO_3$ = 40–75%)	Argillaceous. ($CaCO_3$ under 40%)
Pure limestone.	Clayey limestone.	Slate.
Pure chalk.	Clayey chalk.	Shale.
Pure marl.	Clayey marl	Clay.
	Blast furnace slag.	

The combination of the materials in any two of these groups which will give a mixture of proper composition might be used as the raw material for Portland cement. The only combinations which have been used to any extent in this country are:

Argillaceous limestone (cement rock) and pure limestone.
Marl and clay or shale.
Limestone and shale or clay.
Blast furnace slag and limestone.
Chalk and clay.

While proper chemical composition and physical character are the primary requisites for the raw materials chosen, many other considerations assume great importance when the factors contributory to the economical manufacture of Portland cement are considered. Among these may be mentioned the availability of the deposits, the location with respect to a market and transportation facilities, and also the location with respect to fuel supplies.

5. Limestone. Limestones occur widely distributed throughout the country. When pure, limestone forms the mineral calcite ($CaCO_3$), and all limestones consist essentially of calcium carbonate combined with more or less impurities. The principal foreign elements commonly found are magnesia, silica, iron, alkalies, and sulphur.

Magnesia in the form of carbonate of magnesia occurs very often in limestone, but, since the effort is always made to keep the magnesia content as low as possible in Portland cement, a limestone containing much over 5 per cent of carbonate of magnesia will not be suitable for use.

Silica may be present either alone or in combination with alumina. When alone it may occur as flint in pebbles or in the form of mica, hornblende or other complex silicates. The silica does not readily combine with lime in the kiln, and more than a very small amount renders a limestone unfit for use. Silica combined with alumina is a very common impurity in limestone and such limestones are of great value to the cement manufacturer. Compounds of silica and alumina readily combine with lime in the kiln and the argillaceous limestones are therefore among the most important classes of raw materials for the manufacture of Portland cement.

Iron occurs usually as either the oxide (Fe_2O_3) or sulphide (FeS_2), and less commonly as a carbonate or silicate. Except as a sulphide the iron forms a useful flux, aiding the combination of lime and silica in the kiln. As a sulphide it is injurious and to be avoided if in amounts over 2 to 3 per cent.

The alkalies, soda and potash, commonly occur in limestones in small percentages. Unless present in quantities over about 5 per cent, in which event they may be carried over into the cement with harmful results, they will be largely driven off in the kiln with no consequent effect upon the cement.

Sulphur may be present as iron pyrite or as lime sulphate. In either case its presence is extremely injurious and not over 2 per cent can be tolerated.

The approximate range of composition of limestones used in American Portland cement manufacture is indicated by the following summary:

Component.	Approximate range. Per cent.	Usual percentage.
$CaCO_3$	88.0–98.0	93.0–97.0
SiO_2	0.3– 8.0	0.4– 3.0
$Al_2O_3 + Fe_2O_3$	0.2– 2.1	0.5– 1.3
$MgCO_3$	0.2– 4.2	1.0– 2.5

6. Argillaceous Limestone, Cement Rock. The term "cement rock" is technically applied to a limestone containing about 68 to 72 per cent of lime carbonate, 18 to 27 per cent clayey matter, and not over 5 per cent of magnesium carbonate. Cement rock is a dark gray to black, slatey limestone, softer than pure limestone and consequently more easily ground. As a rule the cement rock must be mixed with a comparatively pure limestone in small percentages. In some cases, however, the cement rock contains an excess of calcareous material, necessitating the admixture of shale or clay.

7. Marl. Marls are deposits of comparatively pure carbonate of lime found in beds of existing or extinct lakes. Organic matter, clay and carbonate of magnesia are the principal impurities found in marls, with sometimes small amounts of sulphur. Marls usually analyze about 90 to 97 per cent $CaCO_3$ and $MgCO_3$, less than 1 per cent SiO_2, less than 1 per cent Al_2O_3 and Fe_2O_3 combined, the balance being made up of small amounts of organic matter, SO_3, etc. When used in the manufacture of Portland cement marls usually require the addition of from 15 to 20 per cent clay. The large percentage of water (often 50 to 60 per cent) usually present in the marl upon arrival at the plant is disregarded in the above statement of composition.

8. Clays, Shales and Slates. Clays, shales, and slate may in general be considered of the same ultimate composition, differing only in the degree of consolidation. All clays are formed from the débris resulting from the decay of rocks, and hence they will differ greatly in composition and physical character. Clays left where rock disintegrates are called residual clays, when transported and deposited by stream action they are sedimentary clays, and when they are deposited by glacial action they are glacial clays. The different classes of clays differ in composition owing to differences in the manner of their deposition. Residual clays are apt to contain fragments of quartz, flint, or lime carbonate, depending upon the character of the rock disintegrated; sedimentary clays in their long water transportation usually have lost all their coarser material and so form a fine-grained homogeneous product; the glacial clays show even less homogeneity than the residual clays and are apt to contain much sand, gravel and pebbles.

Absolutely pure clay is hydrated silicate of alumina or kaolin (Al_2O_3, 2 SiO_2, 2 H_2O). Such a clay is not available for cement manufacture but it is imperative that the clay be as free as possible from gravel and sand. The proportion of silica should not be less than 55 to 65 per cent, and the combined amount of alumina and iron oxide should be between one-third and one-half the amount of silica. The presence of gypsum or pyrite in the clay is injurious, and magnesia and alkalies should not be present in quantities exceeding about 3 per cent.

Shales are clays hardened by pressure, but they have almost invariably been formed from deposits of sedimentary clay and so do not show the irregularities in composition common to most residual or glacial clays. Shales are preferable to soft clay for mixing with limestone because, on account of the similarity in physical character, segregation of the two is less likely to take place. They also carry less water and therefore require less drying. Clay, upon the other hand, is better adapted for use with marl.

The slates are clays which through heavy pressure have solidified in a markedly laminated structure and acquired the property of splitting readily into thin sheets. The slates find only a limited application in the manufacture of Portland cement.

9. Blast-furnace Slag. Three classes of cement which must not be confused are made with blast-furnace slag as one of the ingredients. One is the slag or puzzolan cement made by grinding blast-furnace slag with hydrated lime without subsequent calcination; a second is a true Portland cement made by mixing limestone and slag, grinding the mixture very finely, and calcining the product as in the usual process of Portland cement manufacture; the third is the German "Iron-Portland" cement made by grinding finely together 70 per cent of true Portland cement and 30 per cent of granulated blast-furnace slag.

Blast-furnace slag is a fusible silicate formed during the smelting of iron ore by the combination of the fluxing material with the "gangue" of the ore. The slags used in cement manufacture are those of strongly basic character, the higher the lime the better. The following analysis is typical of the slags used in the manufacture of cements of the second class above given.

Silica	33.10
Iron oxide and alumina	12.60
Lime	49.98
Magnesia	2.45

There is a slight chemical or thermal advantage in the use of slag as a cement material owing to the fact that the lime is present as the oxide (CaO), instead of as the carbonate ($CaCO_3$), meaning therefore a saving of fuel in the kiln. On the other hand this advantage is partially offset by the fact that the granulation of the slag by running the molten material into water results in the absorption of from 15 to 45 per cent of water, which must subsequently be driven off, thus increasing the fuel consumption.

10. Proportioning the Raw Materials. The definition of Portland cement above given (Art. 2) declares it to be a material containing "not less than 1.7 parts by weight of lime to 1 part by weight of silica + alumina + iron oxide, not more than 4 per cent of magnesia, nor more than 1 75 per cent of anhydrous sulphuric acid." The combining of the raw materials in such a manner as to achieve the desired ratio of calcareous to argillaceous materials is not, however, entirely a simple matter, for the reason that Portland cement after calcination is not a mixture of lime and clayey materials, but is what may be termed a "solid solution" of a number of components including silicates and aluminates of lime, but no free lime. The minimum ratio of lime to clayey material prescribed in the definition very roughly expresses the relative proportions in which the two classes of material are understood to combine, and the actual proportions of two given materials which will produce a satisfactory cement can only be determined by a knowledge of the detailed composition of each of the component raw materials, and a further knowledge of the compounds which will be formed during calcination.

The constituent raw materials may be analyzed, but cement chemists do not agree upon the actual constitution of cement. The usual practice is to proceed upon an assumption of the essential constituents of cement based upon the investigations made by M. Le Chatelier and the Messrs. Newberry many years ago. Recent studies of this problem tend to show that neither Le Chatelier nor the Newberrys were entirely correct in their conclusions, but experience has shown that the methods of proportioning which are based upon these conclusions will produce an excellent cement.

The application of a rule based upon complete analyses of the raw materials is not necessary once a plant is well established with fairly uniform raw materials. Usually a fixed standard total percentage of carbonate ($CaCO_3$ and $MgCO_3$) is found by experience with any given raw materials to give a satisfactory mixture, and this standard is thereafter maintained as long as the raw materials remain unchanged.

11. Control of the Mixture During Operation of Plant. The ideal method of control consists in the analysis of both raw materials at the plant before grinding, grinding and mixing according to these analyses, analyzing the mixture as a check, and correcting the mix by the addition of the constituent required before calcination.

In practice, cheaper and quicker methods are adopted as a rule. Either the analysis of the raw material is depended upon and no subsequent effort made to check and correct the mix, or the raw materials are ground and mixed in approximately correct proportions without analysis, and the ground mixture analyzed and then corrected by the addition of the material found deficient.

12. Treatment of Materials Preliminary to Calcination. The calcination of Portland cement materials must invariably be preceded by two processes which may or may not be distinct one from the other: (1) the reduction of the materials to powder; (2) the intimate mixing of the materials in proper proportions. Often the mixing of the materials is accomplished simultaneously with the final pulverization and after the preliminary grinding.

The treatment of the raw materials before calcination follows, in general, one of two possible processes: *The dry process; the wet process.* The latter process is used only when the raw materials consist either of marl and clay or chalky limestone and clay.

13. Theory of Calcination. The principal objects accomplished by calcination of Portland cement mixtures are, in the approximate order of their sequence: the evaporation of water, the dissociation of carbonates of lime and magnesia, the expulsion of the alkalies, the oxidation of ferrous to ferric oxides, and the combination of lime and magnesia with silica, alumina, and ferric oxide to form the silicates, aluminates, and ferrites, which make up the constitution of Portland cement.

Incidentally, contact of the materials with the fuel ash, the kiln lining, and the kiln gases results in the addition of clayey constituents, silica, alumina, and iron oxide, thus very slightly reducing the proportion of lime and magnesia in the finished product.

Most of the moisture is driven off at temperatures only slightly exceeding 100° C. (212° F.). Lime carbonate is dissociated at temperatures somewhat above 900° C. (1652° F.), and magnesium carbonate at temperatures probably[7] between 800° C. (1472° F.), and 900° C. (1652° F.). The formation of silicates, aluminates, and ferrites does not take place at temperatures below about 1100° C. (2012° F.), and for most commercial cement mixtures the attainment of a temperature of about 1550° C. (2822° F.) has been found necessary in order to insure the combination of practically all of the lime with the clayey constituents.

THE DRY PROCESS

14. Quarrying, Crushing and Drying the Rock. The larger part of the material used in Portland cement manufacture is obtained by quarrying.

Quarries are usually opened on a side hill, the rock is blasted down in benches, reduced to manageable size, and removed in small cars running on movable tracks. The steam shovel is often used to load the blasted material upon the cars, and where comparatively soft material is encountered it may be depended upon to excavate the material without blasting.

The obtaining of material by underground workings in shafts or tunnels is rarely employed because of the excessive cost as compared with quarrying. Occasionally, however, a valuable stratum of cement rock, limestone, or shale may be overlaid by a thick stratum of other material, making underground working cheaper than stripping and quarrying. Mining has one advantage over open quarrying in that it is not affected by the adverse weather conditions which usually make quarrying impossible for at least one-fourth of the time.

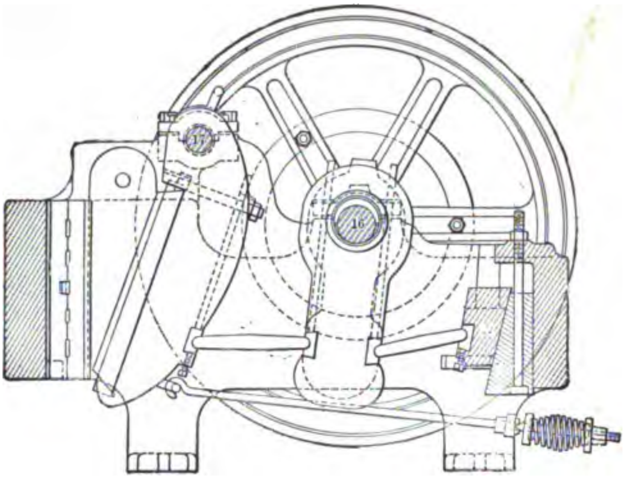

FIG. 1. — Jaw Crusher.

The raw materials employed in the dry process are in general in the form of more or less compact rock, either cement rock and limestone or limestone and shale.

Preliminary reduction is usually accomplished in a crusher of either the jaw type, Fig. 1, or the gyratory type, Fig. 2. A roll crusher, Fig. 3, is occasionally used.

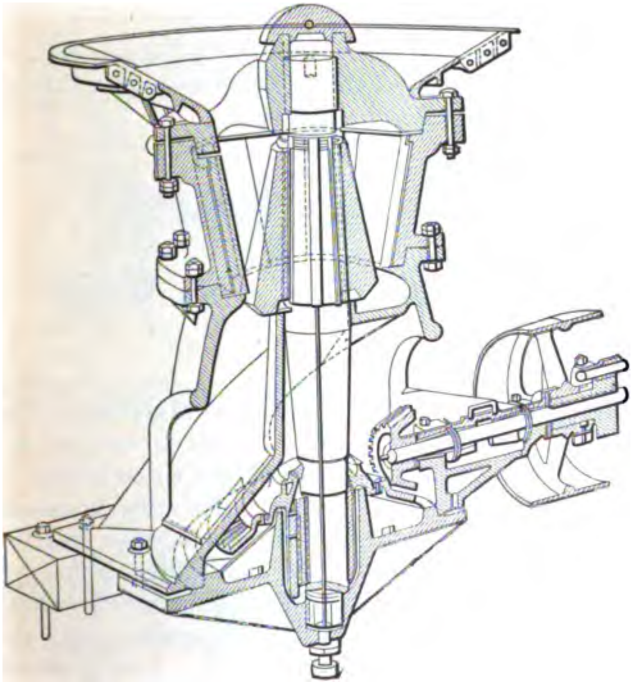

FIG. 2. — Gyratory Crusher.

It is found economical in many cases to use more than one size of preliminary crusher, the smaller machine taking care of the smaller-sized quarry rock and the over-sized material from the larger machine.

The degree to which the preliminary crushing is carried varies at different plants. The general practice, however, is to reduce the rock to a size that will pass a 2 or 2½ inch ring.

The presence of moisture in the rock as it comes from the quarry impairs the efficiency of grinding and pulverizing machinery. It is therefore necessary to dry the rock after crushing.

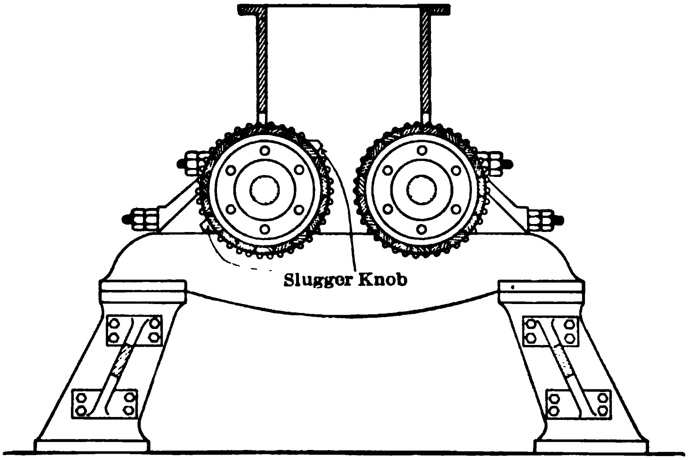

Fig. 3. — Edison Roll Crusher.

The rotary type of dryer Fig. 4 is used almost exclusively in cement mills. From the dryers the material is conveyed to the raw grinding mill where it is ground, mixed, and finely pulverized.

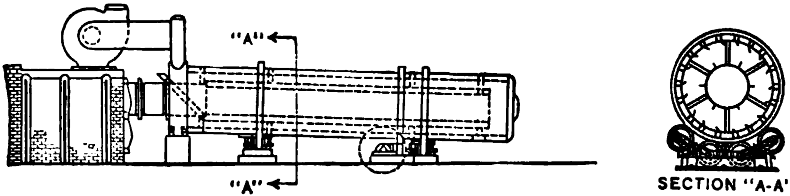

Fig. 4. — Ruggles-Coles Dryer.

15. Grinding, Mixing and Pulverizing the Raw Materials. The further reduction of raw material after drying is almost invariably carried on in two stages. In the first stage the materials, either mixed or separately, are ground to a size varying in the practice of different plants from $\frac{1}{4}$ inch down to $\frac{1}{20}$ inch or less. In the second stage the mixture of the constituent materials is pulverized to the final degree of fineness required. The choice of the type of grinding and pulverizing machinery adopted is dependent upon the character of the raw materials, and the type of equipment originally installed.

Most American plants operating on the dry process use the ball mill, Fig. 5, or the kominuter, Fig. 6, for the initial grinding of the raw mate-

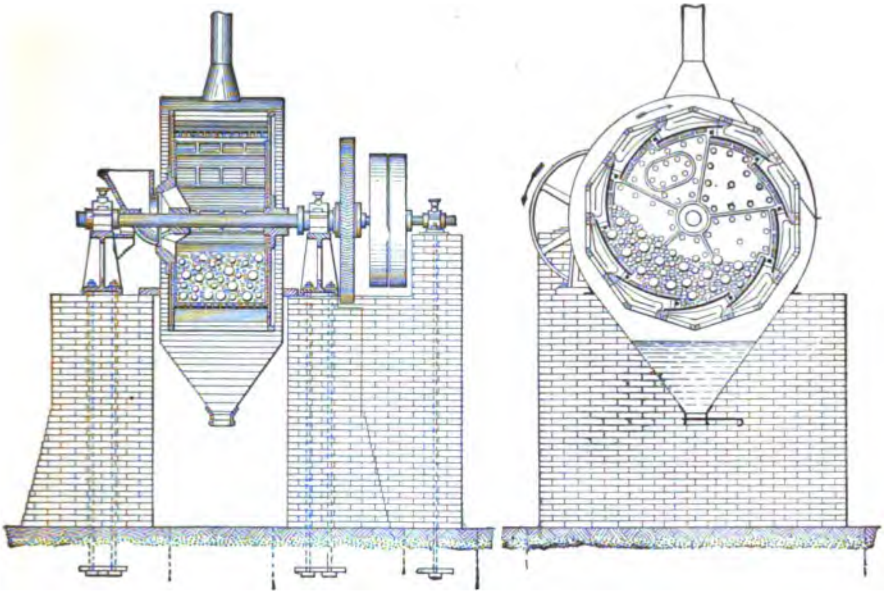

Fig. 5. — Ball Mill.

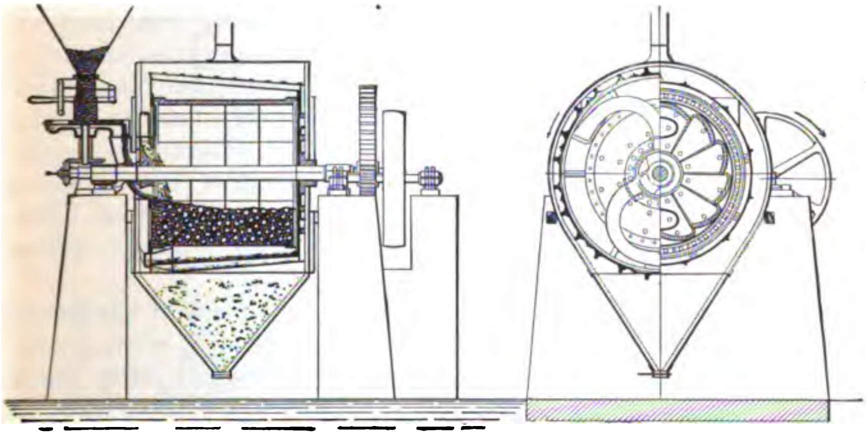

Fig. 6. — Kominuter.

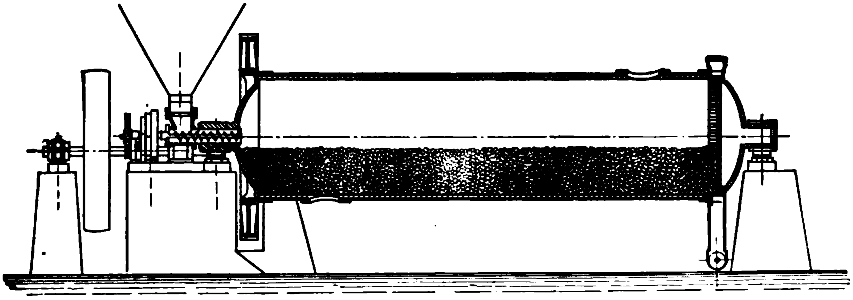

Fig. 7. — Tube Mill.

rial, in conjunction with the tube mill, Fig. 7, or Fuller-Lehigh mill, Fig. 8, for final pulverization. The Griffin mill, Fig. 9, and the Huntington mill, Fig. 10, are also used for final pulverization.

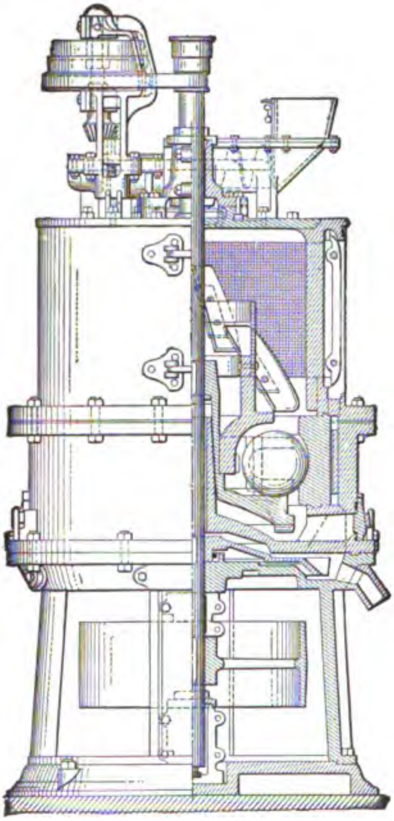

Fig. 8. — Fuller-Lehigh Mill.

The mixing of the two classes of raw material may take place at any one of several points in the process of preparing the material for calcination. The choice depends largely upon the relative physical character of the two classes of material and their uniformity in composition. Two rock ores, such as limestone and shale, or limestone and cement rock, may run so nearly constant in composition that the chemist's analyses made on material as it comes from the quarry may be trusted, and the mixture may be proportioned by weight either just before, or immediately after crushing, without fear of segregation of the two rocks in subsequent handling. Such a combination as a limestone and a clay would give difficulty by segregation, by reason of their differing physical characters, if mixed before being reduced to a finely divided state.

Probably the point in the process where mixing is most often accomplished is immediately after initial grinding and before pulverization, an analysis of the materials having been made after grinding. In the extremely finely divided state attained in the process of pulverization a very intimate mixing without danger of segregation is accomplished.

Very often some type of mechanical weighing and proportioning machine is installed between the stages of initial and final grinding.

Probably no other factor contributory to the production of a satisfactory cement holds so important a place as does the degree of fineness attained in grinding the raw mix.

Since the temperature of calcination is simply a sintering temperature, and not sufficient to fuse the mixture and so produce a homogeneous product, diffusion between the lime and alumina and silica must take place at a temperature usually not exceeding about 1600° C. (2912° F.). The amount of diffusion in a solid is dependent upon three factors, the temperature, the time allowed, and the amount of surface exposed or the state of subdivision of the constituent materials. Fineness of grinding will therefore lead to economy in calcination, since either the duration or the temperature of burning will be lessened by increased fineness of grinding.

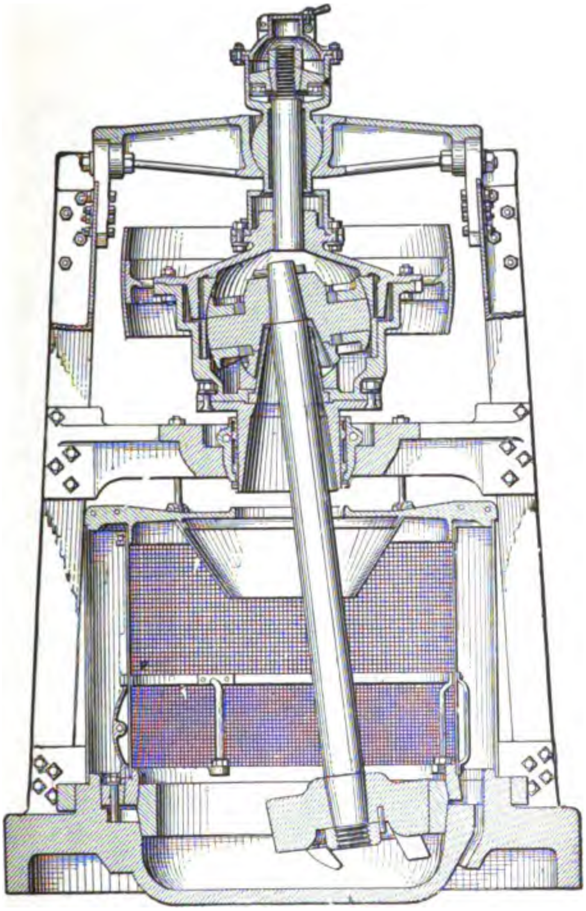

Fig. 9. — Griffin Mill.

On the other hand, if the temperature or duration of burning is not increased to compensate for lack of fine grinding the production of a relatively homogeneous product is impossible. There will be very imperfect diffusion between the constituents of the mix, resulting in the production of a cement lacking volume constancy.

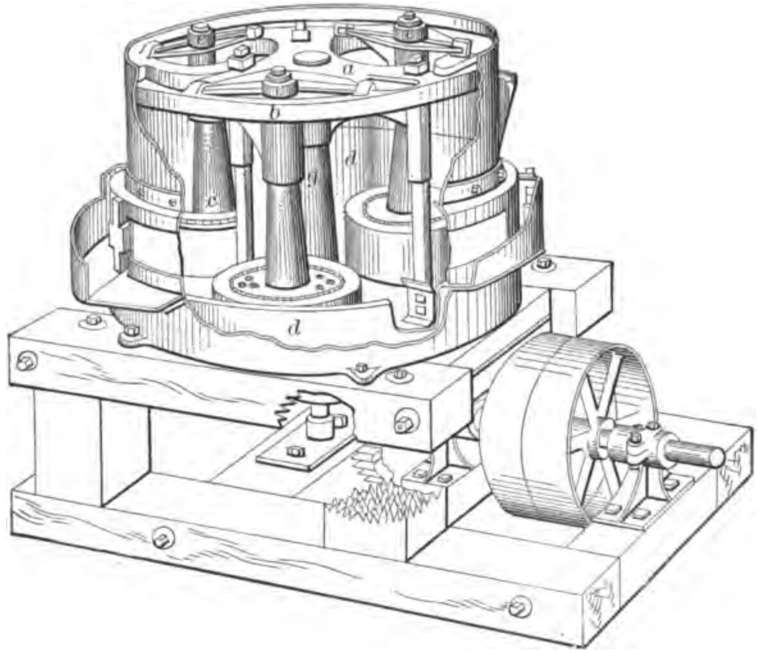

Fig. 10. — Huntington Mill.

The actual degree of fineness attained in practice is somewhat dependent upon the character of the materials used and other local factors. The mixtures of cement rock with a relatively low proportion of limestone, for instance, require less fine grinding than do the mixtures of two pure classes of material such as a pure limestone and a clay or shale.

16. Burning the Cement Mixture. The calcination of the cement mixture is nearly always accomplished in the rotary type of cement kiln, Fig. 11.

Raw material is discharged into the kiln from the supply bins either through an inclined spout, Fig. 12, or a water-jacketed screw conveyor, Fig. 13, running through the stack flue. Usually the feeding device is belt-connected to the kiln drive so that the feeding starts and stops with the kiln. When wet slurry is burned in the kiln it is pumped in from a tank, provision being made to make the rate of supply uniform.

Coal used for kiln burning is usually gas slack and should contain as little ash as possible. Coal is usually crushed in rolls or pot crushers, dried in a rotary dryer, and pulverized in a tube mill, Fuller-Lehigh mill, or Griffin mill.

The pulverized coal is delivered by conveyors from the coal-grinding mill to bins located above and behind the burner end of the kiln. A screw conveyor, Fig. 14, usually carries the coal from the supply bin to a point where it falls into an air injector, where it encounters an air blast which conveys it through a pipe to a nozzle which projects a foot or more into the kiln. The air thus introduced by the blower is only about one-fourth that required for combustion, a large amount being drawn in by the natural draft of the kiln stack through the opening in the hood where the clinker escapes. The pressure of air used is sometimes as high as 60 to 80 pounds per square inch. Natural-draft sys-

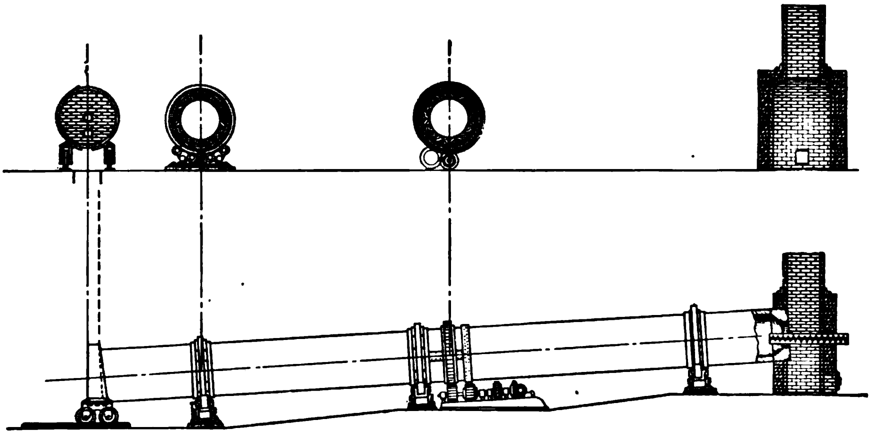

Fig. 11. — 100-foot Rotary Kiln.

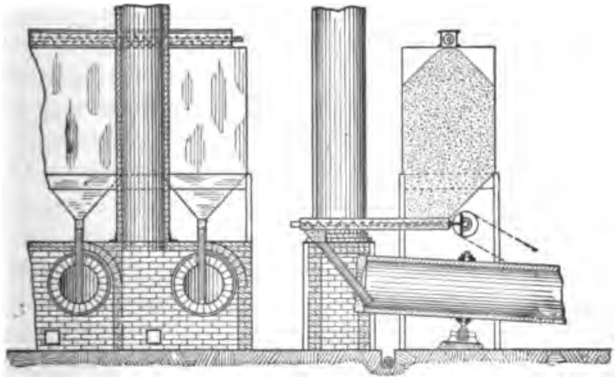

Fig. 12. — Kiln Feed by Spout.

tems, whereby the coal is made to fall in a thin sheet across a slit in the end of the kiln, being carried in by the air sucked in by the natural stack draft, have also been used.

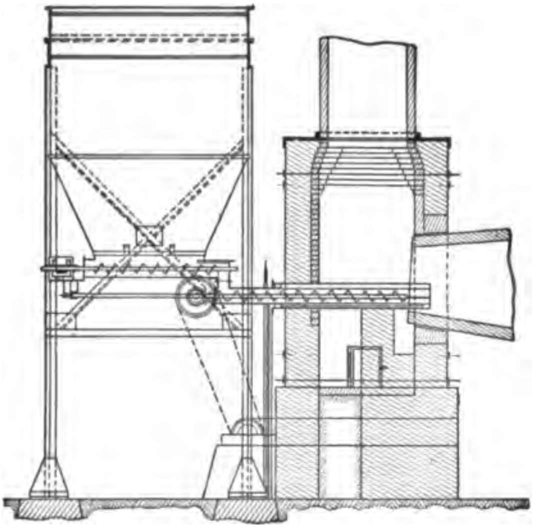

FIG. 13. — Kiln Feed by Jacketed Conveyor.

Crude oil when burned in the rotary kiln is sprayed in by a blast of air from blowers or air compressors. In order to distribute the heat properly in the kiln two or more oil burners are used.

The operation of the rotary kilns requires at all times the attendance of a skilled burner who may look after from two to four kilns. The fuel supply, and the speed of rotation, and hence the temperature of the kiln and degree of burning of the clinker, are under the direct control of the burner. The heat is judged simply by the incandescence of the interior (viewed through darkened glasses) and the degree of burning of the clinker.

Proper burning is determined by the color and appearance of the clinker, the properly burned clinker being a greenish black in color, having a vitreous luster and showing bright glistening specks when just cooled. The lumps are, in the main, from a size of a walnut down. Underburned clinker is brown or has brown centers, and lacks the luster of well-burned clinker. Over-burned clinker has hard brown centers. Over-burned clinker is probably not injurious except for very low lime cements, but over-burning means a fuel waste, and the grinding expense will be increased owing to the greater hardness of over-burned clinker.

Under average conditions an 8 by 100-foot kiln should turn out about 600 barrels of cement per day with a fuel consumption of about 80 pounds of coal per barrel. A 9 by 150-foot kiln should turn out about 750 barrels per day.

The low heat efficiency attained in the rotary-kiln calcination of cement has led to a quite general effort to devise means of utilization of the waste heat.

Heat lost by radiation cannot be utilized, but may be reduced by the placing of a poor heat conductor between the kiln lining and the shell. Heat carried away from the kiln in the stack gases may be reduced in some degree by lengthening the kiln, thereby utilizing a part of this heat in drying and preheating the raw material in the upper part of the kiln.

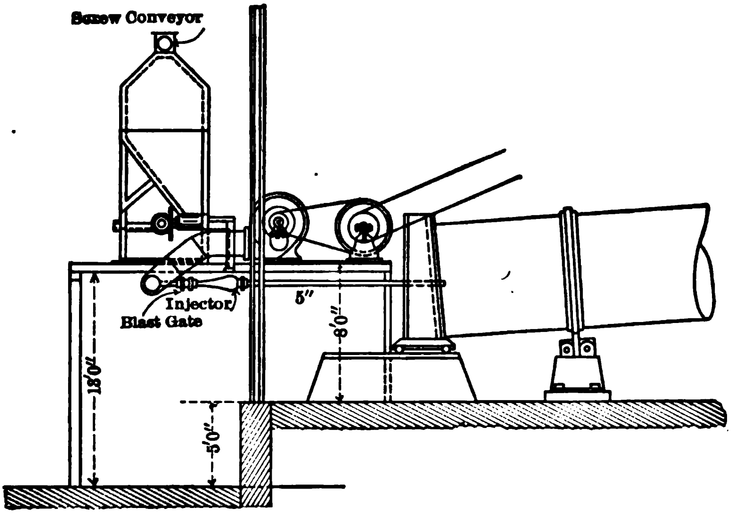

FIG. 14. — Coal Feed for Kiln.

The heat carried by the stack gases has been used in two ways: the first and most common method is for the drying of the raw material in rotary dryers, the second method consists in passing the gases through vertical water-tube boilers, thus generating steam for the power plant. The principal difficulty encountered is the presence of large quantities of dust in the kiln gases, which makes impossible many ordinary methods of heat regeneration.

The utilization of the heat carried off by the hot clinker is quite common. In general the method consists in drawing the air used for combustion in the kiln through the hot clinker in a rotary cooler, thus cooling the clinker and preheating the air.

17. Treatment of the Clinker. The clinker as it issues from the kiln is very hot, and must be reduced to a suitable temperature before being ground. Occasionally it is the practice of cement plants to allow the clinker to cool in piles outside the mill. More generally, however, it has been found advisable to adopt some type of mechanical cooling device which may or may not provide for the recovery and utilization of the heat carried off by the hot clinker.

It is the usual practice to grind the clinker by the same type of grinding machinery used in the raw-material mill, the grinding and pulverizing being accomplished in two separate stages. Three of the principal systems are:

Ball mill, kominuter, or rolls, followed by a Fuller-Lehigh mill.

Ball mill, kominuter, Griffin mill, Kent mill, Sturtevant mill, or Huntington mill followed by tube mill.

Series of rolls.

18. Addition of Retarder. The clinker produced in the rotary kiln process makes a cement which is naturally very quick setting. In order to retard its set sufficiently to enable it to meet commercial requirements, it is the universal practice to add sulphate of lime either before grinding or between the stages of grinding and pulverizing the clinker. The retarder was at one time added in the form of plaster of Paris ($CaSO_4 + \frac{1}{2} H_2O$). Now, however, the universal practice is to add raw gypsum ($CaSO_4 + 2 H_2O$). The gypsum is obtained in the form of lumps crushed to pass a 1-inch ring and is added to the clinker either by hand or by mechanical weighing devices, the quantity used being, as a rule, about 2 per cent, and never exceeding 3 per cent. The retarding agent is the sulphur trioxide present, whether plaster or gypsum be used, and the more frequent choice of the latter is due entirely to the advantage in cost of crude gypsum over that of the dehydrated form.

19. Storing and Packing. The finished cement is stored in stockhouses containing bins holding from 1000 to 5000 barrels each. The bins usually discharge to hoppers and screw conveyors in tunnels below each row of bins.

Cement is either packed in wooden barrels containing 376 pounds net or in cloth or paper bags containing 94 pounds net. Packing is commonly done by some type of semi-automatic machine, which fills, weighs, and seals the barrels or bag.

The Wet Process

20. The Wet Process of Manufacture. In general, the materials handled by the wet process are those of a soft physical character which in their natural state carry high percentages of moisture such as marl with clay or shale.

Marl is usually not only saturated with moisture, but is often covered with water to a considerable depth. Under such circumstances it is obtained by dredging. Usually the excavator is carried on a barge which floats in a channel formed by the dredge in its progress through the basin. The material excavated may be loaded by the dredge upon cars running on tracks alongside the dredged channel, and thence be carried to the mill, or in some cases the material may be loaded by the excavator into hoppers which feed a pug mill, wherein the marl is mixed with additional water so that it may be pumped to the mill through a pipe line. The marl usually reaches the plant in the shape of a thin mud containing about 50 per cent water. It is passed through a separator to remove stones, roots, etc., and then stored in large cylindrical tanks.

The clay upon arrival at the plant is often dried in order to facilitate the determination of the correct proportion to be added to the marl. It is then ground in an edge runner mill (Fig. 15), between mill-stones, or in a disintegrater.

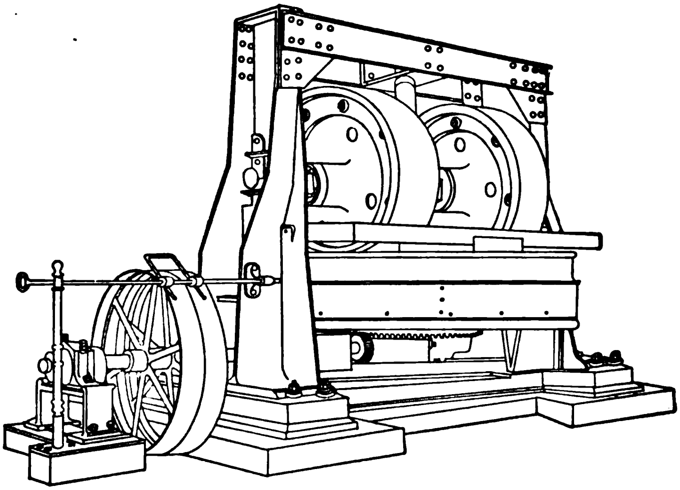

Fig. 15. — Edge Runner Mill.

From the storage tank the marl is pumped either into a measuring tank or a weighing hopper. The ground clay is delivered to bins above, and added to the marl in the proportion determined by analysis of the materials.

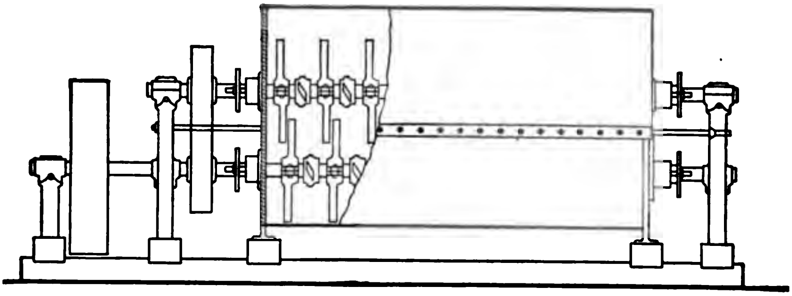

Fig. 16. — Pug Mill.

The mixture is now discharged into a pug mill, Fig. 16, which consists simply of a horizontal cylinder within which two shafts provided with steel propelling blades rotate. The mixture is churned up by the revolving blades, thoroughly mixed, some additional water being usually admitted, and discharged into large vats or dosage tanks where it is sampled, analyzed, and the mixture corrected by the addition of clay and marl. In order to prevent any part of the mixture from settling, it is necessary to provide these tanks with revolving arms with paddles which keep the mass constantly agitated.

The slurry is now passed on to final grinding, which is usually done either in a wet-emery mill or in a wet-tube mill.

The output of the finishing mill is conveyed to supply tanks for the kilns and is charged in without any previous drying. It usually contains from 60 to 65 per cent of water which must be evaporated in the upper part of the rotary kiln. This practice necessarily increases the fuel consumption of the kiln, but has been found to be more practical than the drying of the mixture in a rotary dryer prior to calcination.

SEMI-DRY PROCESSES

21. Semi-dry Processes. In a few instances the wet-slurry process of handling raw materials has been applied to dry raw materials such as limestone and shale, etc.

The pulverized raw materials are passed to a pug mill, the mix corrected in dosage tanks, and the wet slurry fed to rotary kilns, as in the wet process. The only justification for such treatment is the availability of cheap kiln fuel such as crude oil or natural gas. Under such conditions some saving may be effected, since an intimate mixture of the constituents is procured without such fine grinding as is required for the dry process. Where coal fuel must be used, the saving in the grinding department is more than offset by the extra fuel requirement of the kiln for drying the slurry, and the only advantage remaining lies in the fact that as in the wet process, the composition of the mix is under better control than in the dry process.

CEMENT MILL EQUIPMENT

22. Equipment of Raw Mill. *Rock Crushers.* Crushers employed in the initial reduction of the quarry output are either jaw crushers or rotary gyratory crushers. In the first type of crusher (Fig. 1) the reduction is accomplished between a fixed jaw and a hinged reciprocating jaw. In the latter type (Fig. 2) the material falls within a hopper-shaped chamber lined with concave corrugated plates mounted concentrically with the crushing head. The latter is a corrugated steel cone widening toward the bottom, where the annular space between the cone hopper and the crushing head is only large enough to permit the passage of material of a predetermined size. The crushing head is rotated through an eccentric drive which imparts to it an oscillating motion and thereby lessens the liability of choking.

A third class of crusher used for primary reduction consists of two horizontal rolls made to rotate in opposite directions and provided on their periphery with corrugations or large teeth. The best-known crushers of this class are the Edison rolls (Fig. 3), the cylindrical surfaces of which consist of studded plates which grip and crush the rock. In the more recently designed Edison rolls there are provided at two diametrically opposite points on one roll a row of "sluggers," or unusually high knobs, which shatter large rocks sufficiently to bring their size within the angle of grip of the rolls. The capacity of the larger sized Edison rolls is so great that quarry stone up to 7 feet in thickness may be handled.

Dryers. The type of dryer used in cement mills almost exclusively is the rotary dryer. This device consists of a cylinder, 5 to 7.5 feet in diameter, and 40 to 60 feet long, set on a slight inclination, and rotated slowly on roller bearings. The material fed in at the upper end passes slowly through to the discharge end by gravity. Often the interior wall of the dryer is provided with angle irons bolted on parallel to the axis of the cylinder for the sake of facilitating the drying process by lifting and dropping the material as the cylinder revolves. The dried material escapes from the lower end of the cylinder into a conveyor or elevator whereby it is transported to the grinding mills.

The rotary dryer is heated either by the direct combustion of fuel in a furnace located at the lower end of the cylinder, or by the waste gases from the cement kilns. In either case the hot gases pass through the length of the dryer, escaping up a stack set at the upper end.

For drying some classes of material which normally carry very high percentages of water, double-heating dryers are sometimes used. They consist of two concentric cylinders fastened together and revolved on roller bearings. The inner cylinder connects with a furnace at the upper end and is open at the lower end. A fan blower is used to exhaust the gases from the annular outer chamber at the upper end, the path of the gases being therefore down through the central flue and back through the space between the cylinders. The material to be dried is fed in between the cylinders at the upper end, and is caught up by flights on the inside of the outer cylinder and dropped on the hot inner shell. As the cylinder revolves this action is repeated, the drying being further hastened by the hot gases passing through the outer chamber.

The fuel consumption of the rotary dryer is greatly dependent upon the amount of water carried by the material and the character of that material. Marls, because of their high content of organic matter, are especially retentive of moisture. In general the fuel requirements of the dryer vary from about 1 pound of coal per 5 pounds of water evaporated, under the most unfavorable conditions, to about 1 pound of coal per 7 or 8 pounds of water evaporated under favorable conditions.

Grinding Machinery. Centrifugal Grinders and Ring Roll Mills. The Griffin mill (Fig. 9) consists essentially of a steel ring or die against the inside surface of which a heavy steel crushing roll, mounted on a pendulum suspended from a universal joint, is made to roll by centrifugal force. The pendulum is rotated by a pulley at the top and the crushing roll is provided with plows which throw back into the grinding zone the material which has passed the roll into the pit below. The fan mounted upon the pendulum shaft above the roll facilitates the passage of the sufficiently fine material through the annular screen placed just above the grinding zone.

The three-roll Griffin mill or Bradley mill is a modification of the usual Griffin mill, resembling it in every respect except that the single crushing roll is replaced by three rolls.

The Huntington mill (Fig. 10) is somewhat similar to the three-roll Griffin mill. Three heavy crushing rolls are freely suspended from a circular revolving spider. As the head revolves the rolls swing outward through the action of centrifugal force, pressing against an annular die-ring of steel.

The Raymond impact pulverizer resembles the Bradley and Huntington mills except in its detail design.

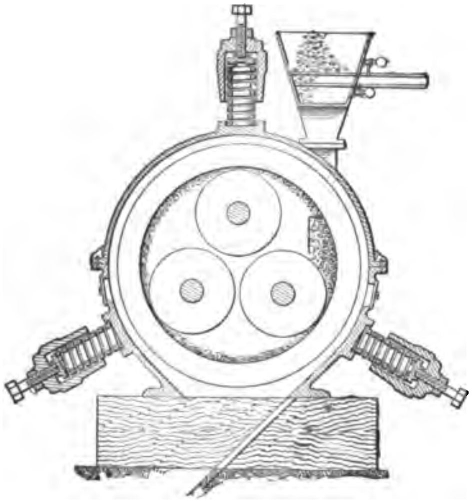

FIG. 17. — Kent Mill.

The Kent mill (Fig. 17) and the Maxecon mill, which latter is simply an improved machine employing exactly the principles of operation of the Kent mill, are ring-roll mills which in some respects resemble the Griffin and Huntington mills, but which employ powerful springs instead of centrifugal force for the grinding pressure. Three convex-faced rolls are mounted on equidistant horizontal axes within the grinding ring. One roll is power driven, and this rotates the ring by traction, the latter in turn rotating the other two rolls. The output of the mill is separated by an auxiliary sifting mechanism, the mill itself having no separating device, and the coarser portion is returned for further grinding.

The Sturtevant ring-roll mill operates in a manner similar to the Kent mill except that the die is positively driven and not through traction by one of the rolls.

The class of mill in which a number of balls are driven around a horizontal annular die is a special type of ring-roll mill. The Fuller-Lehigh mill (Fig. 8) is perhaps the best-known mill of this class. Four balls, weighing 100 pounds each, are impelled around the grinding ring at a speed of 600 feet per minute, by arms secured to a vertical spindle. They press against the grinding ring through centrifugal force. The material is fed into the center of the mill, forced by a fan into the grinding chamber, and the fine material expelled through sieves protected by grids.

Rotary Attrition Mills. Ball Mills, Kominuters, and Tube Mills. The ball mill (Fig. 5) is a short drum rotated at a rate of 20 to 30 revolutions per minute about a horizontal axis, the interior surface being so formed that it consists of a series of steps. The drum contains a number of large steel balls which roll and fall from step to step, thereby crushing and grinding the material fed in through one axis. The stepped plates are perforated, and the material, when sufficiently ground, passes through the perforations onto a screen and finally onto a second screen. The particles too coarse to pass the screens are returned to the grinding chamber through the openings between the overlapping grinding plates. Material which passes the screens will escape into the hopper below and thence to the conveyors.

The kominuter (Fig. 6) is a modification of the ball mill, the principal point of difference being that the grinding plates are not stepped or perforated and the material must pass the length of the drum to an outlet provided at the further end, where it drops on a screen outside the grinding plates. These screens, being conically shaped, slope toward the inlet end, and discharge the over-sized material back into the drum at the center of the inlet end. The material sufficiently ground escapes in the same manner as in the case of the ball mill.

The tube mill (Fig. 7) resembles the ball mill and kominuter in that it is a rotating cylinder partially filled with an abrasive agent. The tube mill is, however, much longer than the ball mill or kominuter. It is usually employed for final reduction of the product of mills of another type.

The tube mill consists of a steel cylinder, 5 to 6 feet in diameter, and 20 to 22 feet long, lined with hardened plates or hard natural stone and mounted on trunnions about which it is slowly revolved at a rate of 25 to 30 revolutions per minute. The abrasive charge usually consists of flint pebbles which fill it approximately to the axis of rotation. The material is fed in through a hollow axis at one end, and either escapes in a similar manner at the opposite end through a hollow axis and screens, or is allowed to escape through gratings at the periphery of the discharge end. Steel balls are occasionally substituted for flint pebbles as the abrasive agent. The fineness of grinding is regulated by the rate of feed, and the capacity for a 5 by 22-foot mill is about 12 to 20 barrels per hour ground to pass 95 to 98 per cent through a 100-mesh sieve. The wet tube mill differs in no essential respect from the dry-tube mill except that the discharge is usually through a screened drum located axially, rather than through perforations located on the periphery of the discharge end.

The Edge Runner Mill. The edge runner mill (Fig. 15) consists of a shallow cast-iron pan in which a pair of wide-tired cast-iron rollers revolve by traction as the pan is rotated, or else the central vertical shaft, which carried the rollers on cranks at right angles to its axis, is itself rotated, the pan being stationary. This latter type is less common. The edge runner mill may be arranged to work with either wet or dry material provided only that the material be of a not too refractory nature. The material is fed into the pan in front of one of the rolls and, after passing the roll, is diverted by scrapers to the perforated plates which surround the pan, then by scrapers again diverted to the pan in front of the other roll, and so the process continues, the size of the output being dependent upon the perforations of the plate, usually being not much under $\frac{1}{4}$ inch, though sometimes under $\frac{1}{20}$ inch. The output of $\frac{1}{4}$-inch material for a 5-foot roll machine working on shale is about 6 tons per hour. The millstones, the rock-emery mill, and the other types of grinding machinery used in the wet process with marl and clay have been described above.

23. Cement Kilns. *Early Kilns.* The earliest type of kiln used for cement burning both in Europe and America was an upright stationary-shaft kiln called a dome kiln or "bottle" kiln, which closely resembled the kilns used for lime burning. The fuel and the raw slurry molded into bricks were charged in at the top and the clinker was withdrawn at the bottom, the process being intermittent.

The first efforts to improve the efficiency of the dome kiln were in the direction of utilization of the hot waste gases of the kiln for the drying and preheating of the raw material. The Johnston kiln attempted to make this saving by a simple arrangement whereby the waste gases of the kiln were led through a long flue within which the briquetted material was sorted and dried. The kiln was still wasteful of fuel in consequence of the fact that its operation was intermittent.

The Hoffman or ring kiln was next utilized in the cement industry. It is very economical of fuel, but requires an excessive amount of skilled hand labor in molding the bricks and charging the kiln.

The next step was the development of shaft kilns which consist of a long vertical flue terminating in a stack, the lower portion of which serves as a preheating chamber for the dried slurry briquettes which are charged with the fuel. A chamber below the preheating chamber serves as a combustion chamber, and the lower portion serves as a cooling chamber for the clinker, the incoming air for combustion being heated thereby.

The shaft kilns are very economical of fuel, but they all suffer under the disadvantage of requiring the briquetting of the raw material and the sorting out of the under-burned and over-burned clinker by hand. The shaft kiln has been replaced by the rotary kiln.

The Rotary Kiln. The modern rotary kiln (Fig. 11) consists of a cylindrical steel shell lined with refractory material and supported on rollers, its axis being slightly inclined from the horizontal. It is revolved on its bearings by a variable speed transmission; its upper end projects into the chimney foundation, which also serves as a dust trap; its lower end enters a movable hood adapted to the discharge of clinker and the entry of fuel and air. Pulverized coal injected by an air blast is most commonly used as fuel, although crude oil is used in some plants.

The first rotary kiln was patented in 1885 in England by Ernest Ransom. It was first made a commercial success in this country, however, the fuel used being petroleum. The use of powdered coal as a fuel was introduced in 1895.

Rotary kilns in use to-day vary in size from 60 feet long and 5 feet in diameter to 240 feet long and 12 feet in diameter. Present practice favors the use of the longer kilns, and few are now installed less than 150 feet long by 10 feet in diameter. The kiln is inclined at a pitch varying from ½ to ¾ inch per foot of length, and is supported by rollers bearing on wide steel tires at from two to five points in the kiln length, the number of supports depending upon this length. Two or more horizontal thrust rollers keep the inclined kiln in place on its bearings. In general the rate of rotation is from one-half to two revolutions per minute. The rate of revolution depends upon the slope of the kiln and the nature of the raw material.

The lining of the kiln is usually a highly refractory magnesite or bauxite brick. The thickness of the lining is variable, being usually from 9 to 12 inches at the lower and hotter end, and 4 to 6 inches at the upper end. In some kilns burning wet slurry the upper part of the kiln is left unlined. The brick are keyed to fit the circle of the kiln, and are held in place by the heavy angle iron which encircles the inside of each end of the kiln.

The hood at the lower end of the kiln is usually mounted on a movable carriage, and the masonry of its front wall is provided with two openings, one for the entrance of the burner apparatus, the other for observation of the operation of the kiln and the insertion of bars for breaking up rings of clinker and making minor repairs to the lining.

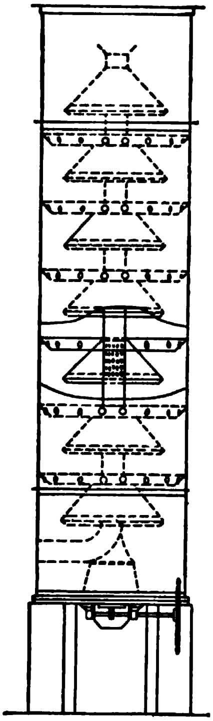

FIG. 18.
Vertical Clinker Cooler.

The lower part of the hood is left partly open to allow the escape of the clinker, which is either diverted to one side into cars, or falls directly onto conveyors. This opening also serves as an air inlet.

24. Clinker Cooling Equipment. Equipment of Finishing Mill. Many of the older plants use an upright gravity cooler (Fig. 18) consisting of a cylinder about 8 feet in diameter and 35 feet high, provided with baffle plates and shelves. The hot clinker is discharged into an elevator pit, where it is sprinkled with water; the elevator discharges it into a hopper at the top of the cooler, whence it falls down over the series of baffles, where it encounters air currents introduced through a perforated vertical pipe in the center of the cooler. A hopper at the base discharges the cooled clinker to a conveyor.

More modern mills employ a rotary cooler which consists of a steel cylindrical shell mounted on rollers in a slightly inclined position and rotated slowly in a manner similar to the operation of the rotary dryer. The rotary cooler is often mounted as an under-cooler directly below the kiln for convenience in direct discharging of the clinker from the kiln to the cooler, the cooling air being drawn into the kiln. The cooler lining consists usually of cast-iron plates bolted to the shell, and shelves are usually provided as in the dryer for the purpose of lifting the material. Water to help cool the clinker is sometimes introduced at the upper end of the cooler and perforations in the shell during the lower 3 feet of its length, 1¼ to 2 inches in diameter, screen the material roughly. An angle iron with the flange projecting inward at the discharge end of the cooler forces the material to escape only through the perforations.

Sometimes the rotary cooler is mounted separately from the kiln, and in such an event it is not usually used to preheat the air for the kiln, but the current of air is drawn through by a stack or blown through by a fan.

The grinding equipment of the finishing mill is usually a duplicate of that used in the raw material mill.

Properties and Uses of Portland Cement

√**25. General.** The value of cement as a structural material depends primarily upon its mechanical strength when hardened. The conditions met with in practical use are, however, so variable as to exclude the possibility of the establishment of standards based directly upon practical experience.

The establishment of the existing standards for physical and mechanical properties has for its object the fixing of values readily determined in the laboratory, for cements found satisfactory in practice, therefore the results of laboratory tests of cement cannot be considered to represent the properties of the material under working conditions, the quantitative results obtained having only a relative value.

The physical properties so utilized for comparative purposes are: specific gravity, fineness, time of setting, and soundness. The mechanical properties similarly used are the tensile and compressive strengths of neat cement and sand mortars.

26. Composition of Portland Cement. A study of a large number of analyses of commercial cements reveals the fact that the range in possible composition is comparatively limited. The following table, which is a summary of detailed analyses of eighty samples of American

Portland cement (representing forty-three brands) quoted by Eckel, gives the extent of possible variations.

Component.	Average of 80 samples. Per cent.		Average of 5 highest brands. Per cent.		Average of 5 lowest brands. Per cent.	
	Actual.	Equiv.	Actual.	Equiv.	Actual.	Equiv.
SiO_2	21.83	(22.34)	24.21	(24.29)	19.69	(20.49)
Al_2O_3	7.43	(7.61)	9.54	(9.69)	4.67	(4.79)
Fe_2O_3	3.31	(3.39)	4.99	(5.12)	1.95	(2.00)
CaO	62.57	....	65.06	....	59.22	
MgO	1.85	....	3.34	....	0.45	
CaO+1.4 (MgO)	65.14	(66.66)	68.27	(68.40)	61.77	(64.80)
Alk	1.15	....	1.93	....	0.55	
SO_3	1.33	....	2.39	....	0.39	

27. Setting and Hardening. When a true hydraulic cement is gauged with sufficient water and then left undisturbed it soon loses its plasticity and finally reaches a state when its form cannot be changed without producing rupture. This change in condition is known as the "setting" of cement and has usually been considered somewhat distinct from "hardening." Setting usually takes place in a few hours or even minutes, while hardening may proceed for months or even years.

SPECIFIC GRAVITY

28. Significance. The significance of the specific gravity of a cement was formerly considered to be its usefulness "in detecting adulteration and under-burning." More recently, investigations have shown that the principal factor influencing specific gravity is the degree of seasoning of cement. Specific gravity tests will not detect under-burning; and will only detect adulteration in the case of a few classes of adulterants. Its importance may, therefore, be considered to be very limited.

29. Specification and Results of Tests.* "The specific gravity of Portland cement shall be not less than 3.10. Should the test of cement as received fall below this requirement a second test may be made upon an ignited sample."

Experiments made by members of the Association of American Cement Manufacturers gave an average of 3.14 for the specific gravity of under-burned cements, and 3.18 for that of hard-burned cements. Few freshly made American Portlands will be found outside these limits.

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*Specifications for cement herein cited are, unless otherwise noted, those of the American Society for Testing Materials adopted 1916.

30. Influence of Thoroughness of Burning on Specific Gravity. Until a few years ago the specific gravity of a cement was considered a valuable indication of under-burning. Experiments have shown, however, that the specific gravity of under-burned cements is only very slightly below that of normally burned cement. Experiments made by Meade upon clinker with varying degrees of burning gave the following results:

Very soft under-burned clinker	3.208
Slightly under-burned clinker	3.222
Normally-burned clinker	3.214
Very hard-burned clinker	3.234

These values all appear high in consequence of the fact that the clinker was ground and tested as quickly as possible after burning, thus preventing the usual lowering in specific gravity by the absorption of carbon dioxide and water from the air.

31. Influence of Adulteration on Specific Gravity. The substances most readily available and practicable for adulteration of Portland cements in this country are natural cements, limestones, clay, slaked lime, slag, sand, and natural volcanic tufa.

Natural cements will lower the specific gravity of the blend in direct proportion to the specific gravity of the natural cement used. Cement rock and limestones could not possibly be used without detection in amounts exceeding 10 to 15 per cent. Clay or slaked lime would similarly be detected if used in more than very small amounts. Slag, having a specific gravity of about 3.0, can be used in very large amounts without detection through excessive lowering of the specific gravity of the blend. Volcanic tufa has been used in the plant operated by the city of Los Angeles in connection with the construction of the Los Angeles aqueduct.

The specific gravity of an ignited sample of cement is invariably higher than that of the original sample, so that the retest provided for in the second clause of the specification will give no indication regarding adulteration. The loss on ignition will serve to detect the presence of an adulterant only in the event of adulteration by addition of raw materials after calcination.

32. Influence of Seasoning on Specific Gravity. The absorption of carbon dioxide and water from the air, which begins as soon as the clinker leaves the kiln and continues as the clinker is ground and the cement stored, results in a material lowering of the specific gravity of cement. Meade quotes the following tests, which show the effect of seasoning upon specific gravity of cement. It will be noted that in each case the loss due to seasoning is regained upon ignition.

EFFECT OF SEASONING UPON SPECIFIC GRAVITY OF CEMENT

Sample No.	1		2		3		4		5		Average.	
Condition.	Dried at 100°.	Not dried.	Dried at 100°.	Not dried.	Dried at 100°.	Not dried.	Dried at 100°.	Not dried.	Dried at 100°.	Not dried.	Dried at 100°.	Not dried.
Freshly made	3.19		3.21		3.16		3.15		3.20		3.182	
After 28 days	3.16	3.11	3.18	3.12	3.14	3.10	3.12	3.09	3.14	3.08	3.148	3.100
After 6 months	3.13	3.08	3.09	3.04	3.12	3.08	3.09	3.03	3.09	3.04	3.104	3.054
Ignited	3.18		3.21		3.18		3.15		3.19		3.182	

33. Summary and Conclusions. Low specific gravity may be caused by adulteration in large amounts; it is not indicative of under-burning; it is indicative of the degree of seasoning. Since seasoning is in general considered desirable for all Portland cements, it is not advisable to reject any cement upon the basis of failure to come up to the specified value of specific gravity unless the history of the cement and its manufacture is known.

Fineness of Grinding

34. Significance. Many experiments have shown that the coarser particles of cement are inert. Even the sieve having 300 meshes per linear inch is not fine enough to pass only active material. This material can be separated out only by some suspension method which retains only the finest impalpable powder or "flour."

"In general, the strength of concrete increases with the fineness of a given lot of cement, for all mixes, consistencies, gradings of the aggregate, and ages of concrete. There is no necessary relation between the strength of concrete and the fineness of the cement, if different cements are considered." *

35. Specification and Results of Tests. "The residue on a standard No. 200 sieve shall not exceed 22 per cent by weight." Very fine cements

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* Effect of Fineness of Cement.—Duff A. Abrams. Proc. A. S. T. M., 1918.

will leave a residue of about 2 per cent on the No. 200 sieve while cements of average fineness leave 10 to 15 per cent.

The percentages of cement for sizes finer than the No. 200 sieve can be found by the use of the air analyser developed by the Bureau of Standards (Fig. 19). The sample of cement placed in the bulb at the base of the tube is agitated by a jet of air through a glass nozzle. The fine part is blown up the tube into the container at the top. A larger size nozzle substituted will blow out the coarser material in turn. If these nozzles are standardized it is possible to separate the fine particles or flour into many sizes.

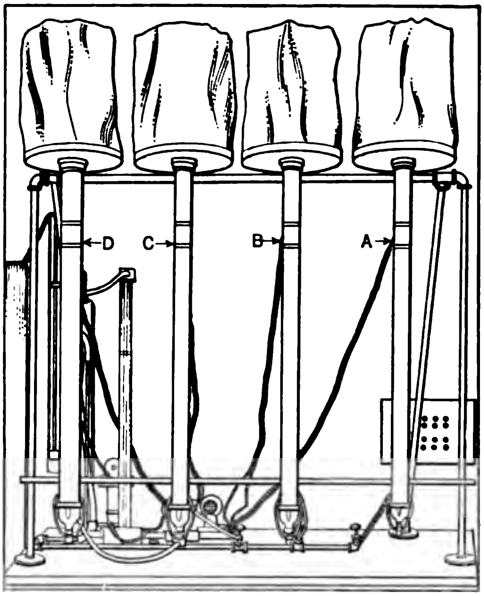

FIG. 19. — Air Analyser.

36. Influence upon Soundness. It has usually been considered that fine grinding improves the soundness of a cement. The extent of the improvement is slight, however, and not such as to justify extremely fine grinding for the sake of improved soundness alone. Meade cites experiments which show that in some cases an unsound cement is made sound by grinding to an impalpable powder; in the majority of cases, however, soundness was attained only by seasoning following fine grinding, making it appear that the beneficial effect of fine grinding is only indirect, in that it affords additional opportunity for seasoning.

37. Influence upon Setting Time. In general, increased fineness of grinding has the effect of making a cement more quick setting. High-alumina cements have their setting time most affected by fine grinding, so that in general the higher a cement is in lime, the more finely it may be ground without reducing the setting time unduly. Extremely fine grinding, or separation of the cement so that the flour is obtained, produces a cement whose set is almost instantaneous. (Flash set.)

Fig. 20 illustrates the effect of increased fineness upon the time of set.

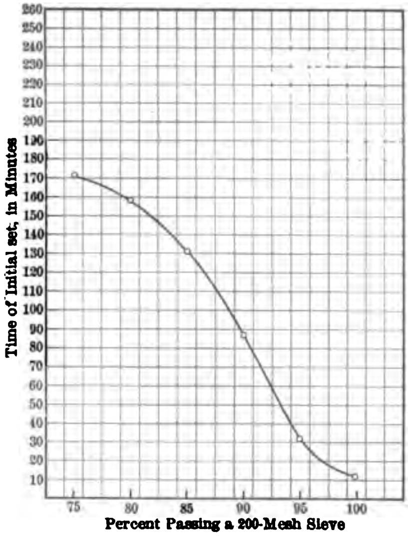

FIG. 20. — Influence of Fineness of Grinding upon Setting Time of Cement. (Meade.)

38. Influence upon Neat and Mortar Strength. Experiments have shown that fine grinding of cement usually lowers the neat strength. On the other hand the sand-carrying capacity and mortar strength of a cement are very considerably increased by finer grinding.

39. Summary and Conclusions. The maximum degree of fineness compatible with reasonable manufacturing costs is desirable. The strength, except in neat tests, is greatly increased and the sand-carrying capacity and mortar strength very materially increased by increased fineness of grinding; the time of setting is materially shortened, but this effect may be lessened and injury in this respect prevented by making the cement as high in lime as is possible without endangering soundness by the presence of excess free lime.

TIME OF SETTING

40. Significance. The rapidity with which a cement sets is simply a criterion by which its suitability for use under given conditions may be established. Absolutely no analogy can be traced between the rapidity with which a cement sets and the strength it will ultimately develop. A cement to be used in submarine construction, for instance, should be quick setting, while a cement to be used under circumstances where rapid handling and deposition in the forms without delay is impossible, may be slow setting.

41. Specification and Results of Tests. "The cement shall not develop initial set in less than 45 minutes when the Vicat needle is used or 60 minutes when the Gillmore needle is used. Final set shall be attained within 10 hours."

So many factors influence the time of setting, such as temperature, amount of water used in gauging, presence of sulphates, etc., that no general statement can be made as to the rate of setting of Portland cements. In general, the higher the temperature the shorter the time of set will be.

The percentage of water used to gauge cement influences its time of set to a very marked degree, a wet mix setting much more slowly than a dry mix. It is on this account that tests for time of set are always made with a paste possessing a standard degree of plasticity (i.e., a normal consistency mix).

The addition of lime sulphate to the clinker before grinding is absolutely necessary in order to retard the set sufficiently to pass the requirements of commercial use. The addition of 1½ to 3 per cent of plaster of Paris or gypsum retards the set, and further additions beyond this point of maximum retardation have the opposite effect.

42. Influence of Seasoning. The effect of seasoning upon the setting time of cement is a source of considerable difficulty for the cement manufacturer. Freshly made cement which is found to be slow setting is frequently found after a few weeks' seasoning to have become quick setting. Conversely, some cements, originally quick setting, become slow setting after seasoning. The latter case is usually less serious than the former, as the cement will probably still be suitable for marketing. In the case of the cement which becomes quick setting upon storage the cause of the difficulty is apt to lie in the composition of the cement and may usually be remedied by increasing the lime content.

43. Summary and Conclusions. The time of set is often an important consideration in the choice of a cement for a particular purpose, and on account of the effect of storage upon the setting time the test should preferably be made after delivery of the cement on the work. The effect of temperature and the percentage of water used in mixing as well as the humidity of the air, is so marked that the determination of the setting time must always be made with extreme care under standardized conditions.

SOUNDNESS

44. Significance. Soundness in a cement implies the absence of those qualities which tend to destroy its strength and durability. The importance of soundness is second to that of no other property of cement. If a cement is ultimately unable to withstand the disintegrating influence of the medium, air or water, in which it is placed, the development of a high degree of strength at the ages usually tested is of no value.

"Unsoundness" is manifested by a lack of constancy of volume, disintegration being caused almost entirely by expansion occurring after the cement has set.

Since any amorphous hydrate shrinks during drying and expands when wet, it is evident that this behavior on the part of the amorphous hydrated constituents of gauged cements must cause shrinkage of neat cement in air and expansion in water. These changes in volume are very much lessened by mixing with inert material as in sand mortar, the degree of volume change being dependent upon the richness of the mortar. The result of the desiccation of the cement is the appearance of fine hair-cracks on the surface of cement or rich mortar used as a plaster or top coat. These fine hair-cracks should not be taken to be an indication of defective cement, but their appearance simply is an indication of the use of too rich a mixture.

"Unsoundness" is due to disruptive action caused by crystallization of certain of its constituents. The principal constituent so involved is lime present in the free state.

The presence of free lime in the cement may be due to an excess of lime in the composition of the cement; failure to calcine at a temperature sufficient to combine all the lime present with the silica and alumina; or failure to grind the raw materials sufficiently fine and mix sufficiently well for the lime to enter combination. If this lime were simply present in its usual condition as an amorphous substance it could never be held responsible for the phenomena exhibited by an unsound cement, because it would become hydrated immediately upon contact with the gauging water and its expansion would be harmless because it would have taken place before setting had begun.

The presence of excess dehydrated magnesia may also be the cause of unsoundness. In this event unsoundness will be observed after a much longer period, since magnesia which has been highly heated remains inert for a long time before undergoing hydration. A long series of experiments following the discovery that the cements involved in several disastrous failures of structures in Europe were very highly magnesian, proved that the addition to cement of highly calcined magnesia produced enormous expansion, while light calcined magnesia was without influence on soundness because of the rapidity with which it became hydrated. In recognition of the effect of strongly calcined magnesia upon the soundness of cement the standard specifications of all countries limit the amount of magnesia to about 5 per cent.

The presence of excess sulphates is also thought to be the cause of unsoundness. The expansion is not due in this case to the hydration of lime sulphate, but is attributed to the formation of calcium-sulpho-aluminate, which is dangerous only in large quantities. The standard specifications limit the SO_3 to 2.00 per cent.

45. Specification. "A pat of neat cement shall remain firm and hard, and show no signs of distortion, cracking, checking, or disintegration in the steam test for soundness." The pat should be about 3 inches in diameter, ½ inch thick at the center and taper to a thin edge. It is stored 24 hours in moist air and then placed in an atmosphere of steam above boiling water for 5 hours. Former specifications required also two more pats, one of which was kept 28 days in moist air, the other 28 days in water at 21° C. (70° F.).

46. Influence of Seasoning. Since unsoundness is primarily due to presence of free lime in cement, exposure to the air will often produce soundness by the conversion of the lime into carbonate of lime or lime hydrate through the agency of the carbon dioxide and moisture always present in the air. Cement originally unsound may sometimes be rendered sound by aëration. Cements which check when tested freshly ground often become sound upon seasoning.

47. Influence of Fineness. Free amorphous lime may probably be so coated with clinker as to be protected from aëration to a large extent, and similarly protected from the water used in gauging for some time, with resultant ultimate unsoundness if such particles of clinker-coated lime are not broken up by fine grinding. Increased fine grinding therefore will often promote soundness in a cement that will not season sound without fine grinding, but the fine grinding should probably be regarded as beneficial only indirectly, in that it makes possible more complete aëration.

48. Effect of Sulphates. The primary effect of sulphates added to cements is greatly to delay the time of setting. Their addition in small percentages does result in appreciable improvement in soundness, as determined in the steam test, but it is probable that here again the effect is only indirectly due to the sulphates, the set being delayed by the latter till the free lime has become hydrated with no resultant evidence of unsoundness. This view is strengthened by the fact that many cements which successfully pass the steam test fail in the air test.

49. Summary and Conclusions. Soundness is the most essential property of cement. Its absence is manifested by cracking and disintegration after cement has set, due to the disruptive force caused by the expansion of certain of its constituents. Soundness is promoted by thorough seasoning, by fine grinding of the raw material and clinker, by keeping the magnesia low and by not exceeding the percentage of sulphates necessary to retard the set sufficiently.

TENSILE STRENGTH

50. Significance. The tensile strength of cement is in itself of very little importance, because cements are rarely depended upon to withstand tensile stresses. The significance of tensile strength as revealed by laboratory tests is therefore limited to the assumption that there exists a fixed relation between tensile strength, compressive strength and soundness. The assumption is often made that the tensile strength of neat cement bears a more or less close relation to the strength of mortars under the same character of stress.

A relation between tensile strength and compressive strength can be established, but it is by no means a constant relation at all ages and it also varies greatly with different cements, and with different mixtures. There is no ground for concluding that a high tensile test of cement at the usual age of testing indicates soundness; often, in fact, it affords ground for the opposite conclusion. The neat tensile strength is no indication of the strength of the cement in mortars and concrete.

51. Neat Cement. Tests of tensile strength are dependent upon a great many factors which influence the accuracy of the results. Perhaps the greatest of these is the personal equation. In addition to the disturbing personal factor, tensile strength is greatly influenced by the amount and the temperature of gauging water, the method of mixing and molding in general, the temperature and humidity of the air, the form of briquette, the design of the testing machine and the grips, and the manner of storage of the briquettes prior to testing. All of these factors have to do with testing operations. The actual tensile strength, the conditions of testing being considered constant, is dependent primarily upon the composition of the cement; secondarily, upon the temperature of burning, and the fineness of grinding. Fig. 21 shows the average tensile strength, neat, of seven representative brands of Portland cement.

FIG. 21. — Tensile Strength of 7 Portland Cements Neat. (Structural Materials Laboratory Tests.)

52. Influence of Lime Proportion on Tensile Strength. An increase in the proportion of lime yields a stronger cement until a point is passed beyond which further additions mean the presence of excess free lime with consequent unsoundness. High-limed cements which are still perfectly sound are slow setting, but attain their maximum strength early, sometimes showing retrogression in tensile strength after as short a period as seven days and usually showing retrogression after longer periods.

This retrogression is not noted, however, in compression tests, and it appears possible that the low tensile test results are due to the brittleness of such cements and the difficulties in the way of so gripping the briquettes as to make the stress a pure tensile stress.

53. Influence of Temperature of Burning on Tensile Strength. The temperature of burning affects the tensile strength chiefly indirectly, in that the temperature of burning must be high for high-limed cements and therefore high for cements of high tensile strength. Under-burning will result in weak cement, but over-burning probably has no injurious effects so far as the quality of the product is concerned.

54. Influence of Fineness of Grinding upon Tensile Strength. Fine grinding is not beneficial to neat tensile strength, but materially improves the strength of mortars.

TENSILE STRENGTH OF SAND-CEMENT MORTARS

55. Significance. The discussion regarding the significance of tensile tests of neat cement largely covers the subject of tensile tests of mortars. If tensile tests of cements must be depended upon, the briquettes should be mortar briquettes, since in the neat tests one of the most important properties of cement, the ability to adhere to the surfaces of foreign particles and masses, is not determined.

56. Specification. "The average tensile strength in pounds per square inch of not less than three standard mortar briquettes composed of one part cement and three parts standard sand, by weight, shall be equal to or higher than the following:

Age at test, days.	Storage of briquettes.	Tensile strength, lbs. per sq. in.
7	1 day in moist air, 6 days in water	200
28	1 day in moist air, 27 days in water	300

"The average tensile strength of standard mortar at 28 days shall be higher than the strength at 7 days."

"The sand to be used shall be natural sand from Ottawa, Ill., screened to pass a No. 20 sieve and retained on a No. 30 sieve."

The amount of water used in gauging mortar for briquettes is very carefully standardized and is based upon the water necessary to bring the neat cement to normal consistency.

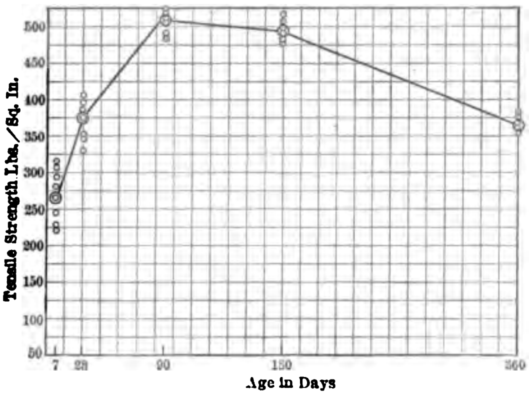

Fig. 22. — Tensile Strength of 7 Portland Cement Mortars 1 : 3. (Structural Materials Laboratory Tests.)

The average tensile strength in 1 : 3 standard mortar of the same seven brands of cement whose average neat strength was noted in Art. 51 and Fig. 21 is shown by the curve of Fig. 22.

57. Effect of Fineness of Sand upon Mortar Strength. The size and granulometric composition of a sand have a marked influence upon the strength of mortars. The relation between fineness of sand and tensile strength of mortars is shown in Figs. 23, 24 and 25, which are plotted from tests made on 1 : 1, 1: 2, and 1: 3 mortars in the laboratories of the College of Civil Engineering, Cornell University.

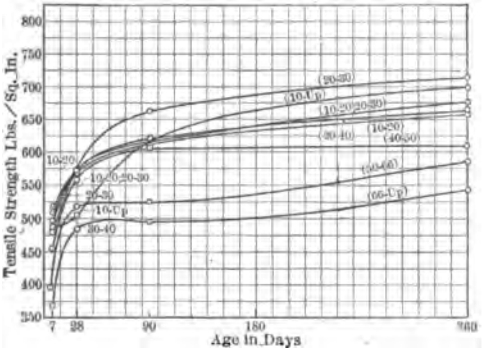

Fig. 23. — Effect of Fineness of Sand upon Tensile Strength of 1 : 1 Mortar. (Tests of R. P. Davis.)

58. Influence of Mica in Sand upon Tensile Strength of Mortars. The detrimental effect of the presence of even small percentages of mica added to 1: 3 mortars made with standard Ottawa sand is shown by the curves of Fig. 26.

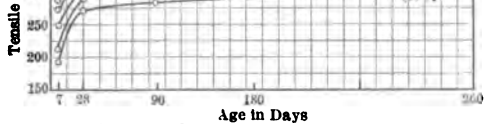

Fig. 24. — Effect of Fineness of Sand upon Textile Strength of 1 : 2 Mortar.

" This loss of strength, which is very considerable even if there is only a slight amount of mica present, is due to two causes: first, because of its irregular shape the percentage of voids is increased, and second, on account of its smooth surface which prevents proper bonding."

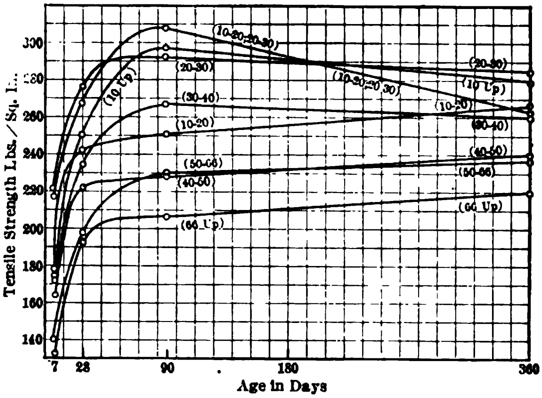

FIG. 25. — Effect of Fineness of Sand upon Tensile Strength of 1 : 3 Mortar.

59. Influence of Cleanliness of Sand upon Strength. Sand used for structural purposes is never really clean unless washed on the work, and the importance of this factor should be fully recognized in concrete construction. The character of the impurities in sand is more important than the amount. If largely vegetable loam, the danger is in direct proportion to the amount of organic matter in the loam or silt. Experiments made by Mr. Sanford E. Thompson led to the conclusion that to be injurious the organic matter must constitute over 10 per cent of the silt and at the same time over 0.1 per cent of the sand.

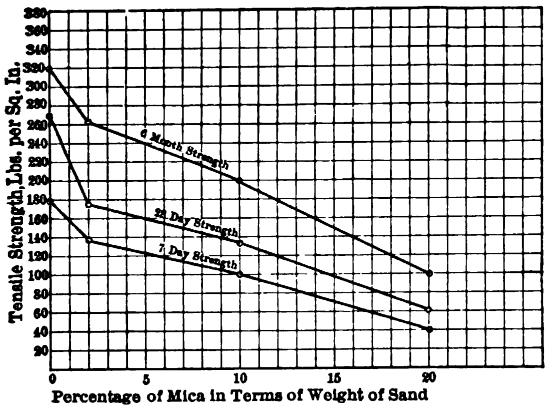

FIG. 26. — Effect of Mica in Sand on Tensile Strength of 1 : 3 Mortars. (Willis.)

If the impurities in sand are of a mineral character, such as clay, the effect is dependent upon its state of subdivision and the uniformity with which it is distributed through the sand. In most laboratory tests the addition of clay has been found to be harmless and often beneficial up to a certain limit. This limit has usually been found to be from 5 to 10 per cent of the sand.

The results attained in laboratory tests should not be taken to indicate that similar percentages of clay will be beneficial or harmless in naturally clayey sands used in practice for concrete or mortars. The manner of distribution and degree of fineness of the clay will be the determining factors, and the amount permissible will in general not approach the above limits.

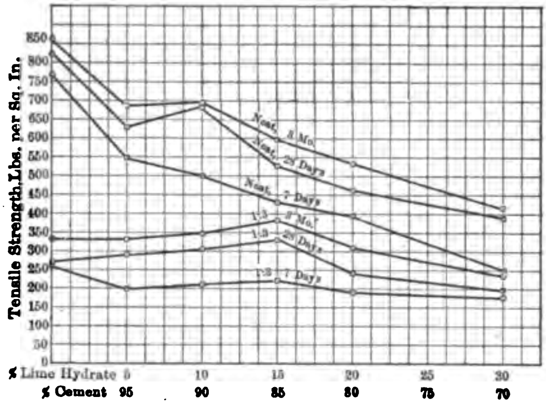

FIG. 27. — Effect of Hydrated Lime on Tensile Strength of Portland Cement and Mortars. (Gardner.)

60. Effect of Addition of Hydrated Lime to Cement and Mortars. The addition of hydrated lime in small percentages to cement and mortars usually has a very appreciable effect upon the resultant tensile strength shown by tests. The curves of Fig. 27 illustrate the injurious effect in the case of neat cement and the slightly beneficial effect, in amounts up to 15 per cent, in the case of 1: 3 mortar using standard Ottawa sand.

Investigations of the effect of additions of lime hydrate upon the strength of cement mortars have not invariably shown that additional mortar strength is attained. Tests made by H. S. Spackman indicate that the addition of 10 per cent of hydrated lime has no marked effect upon either the tensile or compressive strength of mortars.

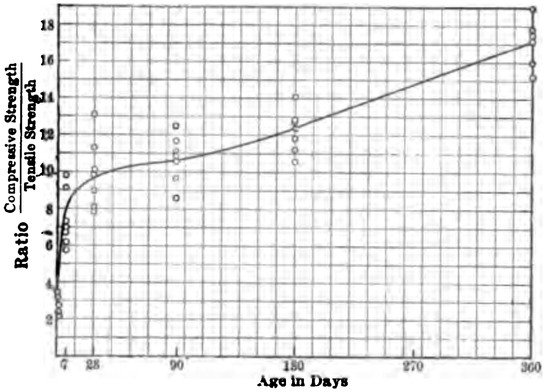

FIG. 28. — Ratio of Compressive to Tensile Strength of Neat Portland Cement.

The addition of hydrate makes a fat, viscous mortar in which the sand and cement will not separate to as great an extent as when Portland cement is used with sand alone. This tends toward the production of a mixture of greater uniformity and with less voids, therefore securing a mortar of more uniform strength. Hydrated lime is an excellent waterproofing substance for incorporation in mortars and concrete.

61. Relation between Tensile and Compressive Strength. The existence of a more or less definite and constant relation between the tensile strength and the compressive strength of cement has been often asserted. Such a relation is the only reason for the adoption of tensile strength as a criterion of the value of a material for use in situations where it will be subjected only to compressive stress.

The results of tests made in the Structural Materials Laboratory at St. Louis, Mo., shown in Figs. 28, 29 and 30 for neat cements and for 1 : 3 mortars give an increase in the ratio of strengths with the age.

FIG. 29. — Ratio of Compressive to Tensile Strength of 1 : 3 Mortar. (standard sand.)

These curves support the opinion that the ratio of compressive to tensile strength of cement mixtures, neat and mortar, is dependent upon so many factors that the tensile strength cannot in general be taken to be more than a very approximate indication of the probable compressive strength of the same cement.

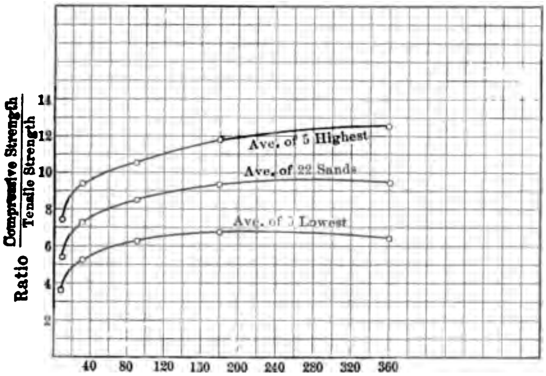

FIG. 30. — Ratio of Compressive to Tensile Strength of 1 : 3 Mortar. (22 natural sands.)

62. Tensile Strength and Soundness. The fallacy of the belief, often held, that a cement which shows up well in the early neat tests of tensile strength is not apt to fail to meet satisfactorily the conditions of structural use, through lack of constancy of volume, is illustrated by Fig. 31, which is based upon tests made by Mr. W. P. Taylor. These curves are derived from over two hundred nearly consecutive tests of a single brand of Portland cement, one hundred of them failing in the soundness test, and one hundred passing.

It will be noted that the early strength of the neat tests of those samples failing to pass the test is much the greater, while the opposite is true in the case of the mortar samples.

63. Summary, Tensile Strength. Tensile strength has little significance as a criterion of the suitability of a cement for use. The mortar tests should always be given greater weight than tests of neat strength, and compressive tests should always be made the criterion of mechanical strength where conditions permit.

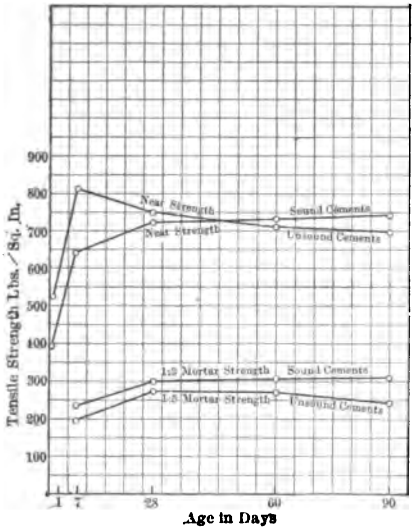

FIG. 31. — Relation Between Tensile Strength and Soundness. (W. P. Taylor.)

Fine grinding increases the mortar strength but reduces the neat strength.

Mortars are stronger if the sand is comparatively coarse; mortars of greatest density usually show highest tensile strength; mica in sands is injurious to mortar strength; dirt in a sand is dangerous in proportion to the amount of organic matter present, as little as 0.1 per cent having been found injurious; clay, if finely divided and uniformly distributed, has been found usually beneficial in laboratory tests, in amounts not exceeding 5 to 10 per cent; in practice the permissible amount in a sand may be much lower.

Hydrated lime in small percentages decreases neat strength but may increase mortar strength slightly.

The ratio of compressive to tensile strength is dependent upon too many factors to make the latter a safe indication of the probable value of the former; high tensile strength is no indication of soundness, unsound cements often showing high early strength in neat mixtures, though not in mortars; the ratio of neat to 1:3 standard mortar strength is very variable, depending on the percentage of impalpable powder in the cement; the rate of increase in tensile strength is dependent upon the early strength values; a cement testing low at 7 days may show a high rate of increase at 28 days, and vice versa; retrogression in neat and also mortar tensile strength at six months is quite general.

Compressive Strength

64. Significance. Compressive strength is the best criterion by which to judge the value of a cement. The conditions of testing more nearly approximate the conditions met by the material in use than is the case in any other laboratory test, and the results therefore should have great weight in the selection of a cement or the determination of quality.

65. Results of Tests. Figs. 32 and 33 show the compressive strength of the same seven representative brands of cement, the tests of which were used to illustrate the typical values of tensile strength.

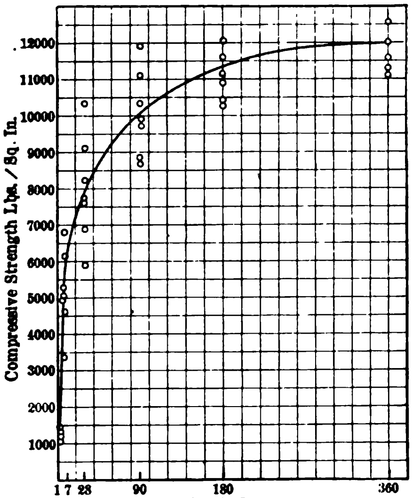

FIG. 32. — Compressive Strength of 7 Portland Cements, Neat.

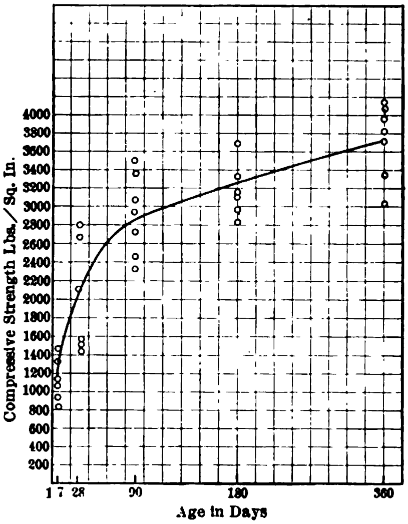

FIG. 33. — Compressive Strength of 7 Portland Cement Mortars 1 : 3 Standard Mortar.

The discussion under the head of tensile strength has for the most part a direct application in the consideration of compressive strength. Retrogression in the compressive strength of neat mixtures or mortars is very uncommon.

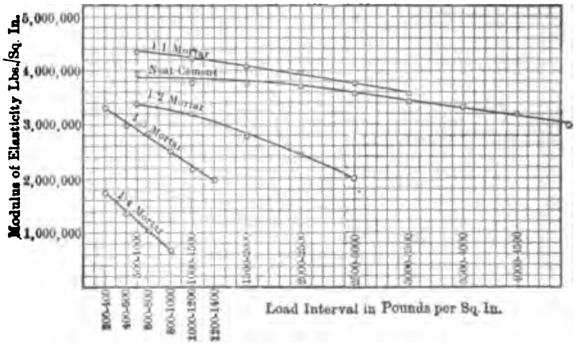

FIG. 34. — Modulus of Elasticity of Cement and Standard Sand Mortars.

66. Modulus of Elasticity of Cement and Mortars. The modulus of elasticity of cement and mortars has seldom been determined. It has been shown that the modulus is not a constant for a given specimen, but decreases rapidly with increased load. In general the modulus is found to be lower as the mixture becomes leaner, and for a given mixture increases with age. Fig. 34 gives values of the modulus determined by tests made at the age of three months for a single brand of cement in several mixtures. The values given here are slightly higher than the average cements and mortars show at this age.

67. Shearing Strength of Cement and Mortars. The shearing strength of mortar is important not only because of the intimate relation between shearing strength and compressive strength, but because of the fact that mortars and concretes are often subjected to shearing stress when used structurally. Very few tests of shearing strength have been made, however, because of the difficulty found in subjecting a specimen to a purely shearing stress.

The following table has been prepared from Bauschinger's report of tests published in 1879. The specimens used were prismatic in shape, the cross-section being 2.4 inches by 4.8 inches. The specimens were stored in water. Each result in the table is the average of nine tests. For comparative purposes the tensile and compressive strengths of the same mixtures are given in the table. All stresses are given in pounds per square inch.

SHEARING STRENGTH OF CEMENT AND MORTARS

Mix.	Tension.			Compression.			Shear.		
	7 day.	28 day.	2 year.	7 day.	28 day.	2 year.	7 day.	28 day	2 year.
Neat	224	294	292	1910	2490	4680	271	346	415
1 : 3	95	169	272	880	1040	3340	116	188	375
1 : 5	64	103	232	537	977	2960	77	131	364

The shearing strength will in general be dependent upon the same factors as the tensile and compressive strength.

The Adhesive Strength of Cement and Mortars

68. Adhesion to Steel. The adhesion of cement and mortar to steel is important in the consideration of reinforced concrete and the holding power of anchor bolts, etc., which are imbedded in cement or mortar, or are grouted in place in drilled holes. Few tests are available to show the adhesive power of cement and mortars on steel, though many tests have been made to determine the same property for concretes. The following data are quoted by Sabin from tests made with an ordinary river sand.

Each figure is the average of from five to fifteen tests made when the mortar was one month old, the imbedded steel being plain round rods.

ADHESION OF CEMENT AND MORTAR TO IRON RODS

Mixture.	Neat.	1 : 2	1 : 3
Average adhesion, lbs. per sq. in. of contact	313	264	111

69. Adhesion to Brick. The adhesion of cement and mortar to brick is of importance in all brick masonry construction. The following table has been constructed from a series of tests made by Sabin. In each case two bricks were cemented together flatwise with a ½-inch mortar joint and pulled apart in tension after a given interval. The specimens were stored in damp sand after the first forty-eight hours, and tensile tests of the same mortar were made for purposes of comparison on briquettes stored in the same manner. The consistency of the mortars was rather more moist than normal.

ADHESION OF CEMENT AND MORTARS TO BUILDING BRICK

Adhesion or cohesion.	Age. Months.	Tensile strength, pounds per square inch, of mortars containing parts sand to one cement.				
		None.	½	1	2	3
Cohesion	1	632	596	589	409	270
Adhesion	1	48	42	24	20	11
Cohesion	3	676	728	694	423	325
Adhesion	3	64	52	41	24	12
Cohesion	6	723	764	679	524	374
Adhesion	6	50	56	39	20	14

It will be noted that in general there is a fairly close relation between tensile strength and adhesion at all ages, the ratio of adhesion to cohesion being about 8.6 for neat cement, 7.1 for 2 : 1 mortar, 5.2 for 1 : 1 mortar, 4.8 for 1: 2, and 3.8 for 1: 3, showing that the addition of sand decreases the adhesion to brick more rapidly than it does the cohesive strength. Tests made with mortars to which lime paste had been added showed that the addition of 10 per cent lime increased the adhesive strength 120 to 140 per cent; 16.7 per cent lime, 130 to 160 per cent; 25 per cent lime, 110 to 120 per cent; and 50 per cent lime, 75 to 80 per cent. The addition of lime increased the ratio of adhesion to cohesion in all percentages, since only small percentages of lime are even moderately beneficial to tensile strength and large percentages are detrimental.

70. Adhesion of Mortar to Various Materials. The adhesion of mortars to various building materials is a matter of much importance in construction work, but it has been little investigated. Fig. 35 gives the results of tests made by Gen. Wheeler.

Discs of the material concerned were prepared, 1 inch by 1 inch square and $\frac{1}{4}$ inch thick, and inserted in the center of the briquette molds, which were subsequently filled with mortar and tested in the usual manner in tension.

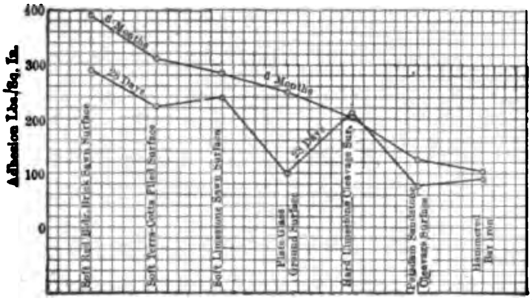

Fig. 35. — Adhesive Strength of Portland Cement. 1 part cement, 1 part crushed quartz. (Wheeler, Report of Chief of Engineers, 1895.)

71. Abrasive Resistance of Cement and Mortars. This property of cement and mortars is primarily of importance in the determination of the best mortar for use in the top coat of concrete floors, walks, and pavements. Resistance to abrasion will always be dependent not only upon the cement, as regards the tenacity with which it clings to the sand grains, but also upon the hardness of the sand used. Abrasion either wears away the cement and the sand particles or it pulls the sand grains out of the cement matrix.

With soft sand particles the resistance to abrasion with a given cement decreases constantly as the percentage of sand is increased. With hard sand grains the abrasive resistance increases as the proportion of sand increases, until the volume of cement becomes relatively too small to bind the sand grains together thoroughly. This limit is usually reached when the mortar contains about two parts of sand to one of cement.

72. Permeability and Absorptive Properties of Cement Mortar. The permeability of mortar is a measure of the rate at which water under a given pressure will pass through a given thickness of the material. The absorptive properties of a mortar constitute a measure of the rate at which moisture will be absorbed when the mortar is exposed in damp situations or covered with water under negligibly small heads.

Permeability is an important consideration where watertightness of walls, etc., is required and percolation of water is not admissible.

Absorptive properties of a mortar determine its value as a dampproofing coat, particularly in the event of its use as a mortar over metal lath, which must be protected to prevent corrosion. In view of the disintegrating effect of expansion and contraction of mortars used as a plaster, etc., the moisture content should not vary greatly.

The determining of precise information concerning each of these properties is dependent upon a standardization of methods of conducting tests. Such standard methods have not yet been adopted, and it is therefore impossible to quote data as to the absolute permeability or absorptive power of mortars. Such tests as have been made tend to show that:

Permeability decreases rapidly for all mixtures with increase in age of the specimens when tested; permeability decreases considerably with the continuation of the flow; permeability increases with the leanness of the mixture, the dryness of the mixture, and increased coarseness of the sand.

Absorption is dependent upon the same factors: it decreases with the age of the mortar as a rule, but not as rapidly as does the permeability (especially with the leaner mixtures); it decreases but slightly with increased richness of the mixtures; and the wetter mixtures are slightly less absorptive than the dryer mixtures.

73. The Expansion and Contraction of Cement Mortars. Changes of temperature are accompanied by changes in volume in cement mortars as in other structural materials. The temperature coefficient for mortars has been found to be 0.0000099 per degree C. (0.0000055 per degree F.).

Other volume changes due to the chemical processes of setting and hardening, and still others caused by variation in the moisture content of cement, constitute important considerations in the use of mortars and concrete. Professor A. H. White of the University of Michigan has made an experimental study of this question and the following short discussion is based upon his work.

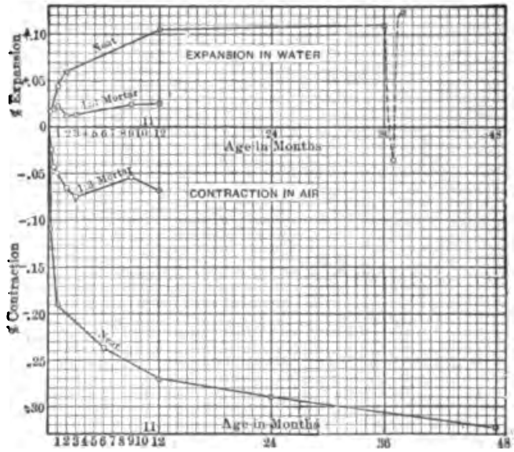

FIG. 36. — Linear-expansion and Linear-contraction of Bars of Cement and 1 : 3 Standard Mortar. (Tests of A. H. White.)

Fig. 36 shows the average percentage of linear shrinkage of bars of neat cement kept in air for periods up to four years, and also the average linear expansion of bars kept in water for three years. Four different brands of Portland cement, all passing standard specifications for constancy of volume, were used.

It is evident that in the case of neat cement fully one-half the total expansion or contraction comes in the first month, and there is very little change after one year. The expansion and contraction of 1:3 mortar was found to be very much less than that of neat cement, and in general, at the end of one year amounts to from one-quarter to one-third that of neat cement.

When bars of cement or mortar, after lying in water for three years, were allowed to dry in air at room temperatures, they gradually contracted till, at the end of two months, they had shrunk not only to their initial volume, but in most cases showed a considerable further contraction. When the bars so air-dried were again immersed in water they recovered in one day 90 per cent of the length they had lost in sixty-five days' air drying, and in most cases their length within one month exceeded that which they showed at three years, before having been air dried.

Properties of Concrete

74. Compressive Strength. The compressive strength of concrete is dependent upon many factors which vary widely. All of the factors which affect the strength of cement mortars naturally affect concrete in a similar manner. The density, the character and granulometric composition of the aggregate, the consistency of the mixture, the actual mechanical strength of the stone of the aggregate, and the conditions of mixing, deposition, and aging all have a direct bearing upon the strength of concrete. Thus it is impracticable to attempt to state the average strength of given mixes of concrete at definite ages in more than a very general way. For any work of large extent it is always desirable to make a series of tests of the actual concrete used, the test specimens being, whenever possible, molded from the concrete actually mixed for the work. If this is not possible, the materials employed

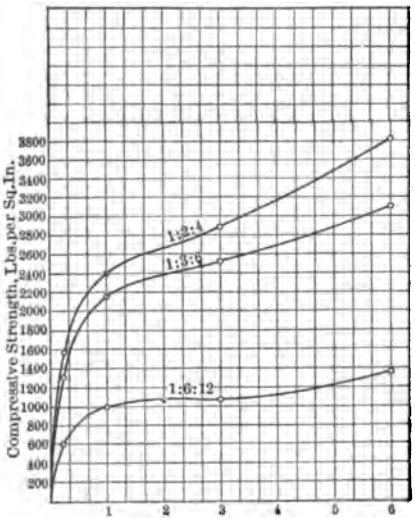

FIG. 37.—Compressive Strength of Concrete, Watertown Arsenal Tests. 12-Inch Cubes.

should be used, and the conditions of mixing made to approximate working conditions as closely as possible.

Fig. 37 gives an approximate idea of the strength of concretes. The curves express the average results of compressive tests at the Watertown arsenal of five concretes made from different brands of Portland cement.

Fig. 38 shows a series of long-time tests of 8-inch concrete cubes of 1:2:4 mix made by Prof. Mills. The curve is representative of the results of similar tests made with several different brands of cement. The slight drop in strength after long intervals was found characteristic of practically all tests.

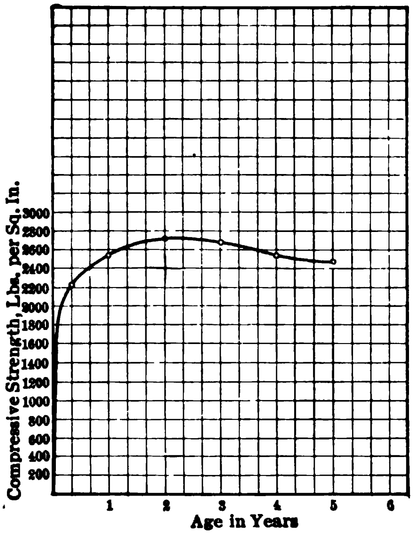

FIG. 38. — Compressive Strength of Concrete, Long Time Tests. 1 : 2 : 4 Mixture. 8-Inch Cubes.

Concrete is usually tested in the form of cylinders 8 inches diameter by 16 inches long, or 6 inches diameter by 12 inches long.

75. Tensile Strength. The tensile strength of concrete is a property of limited importance because, being low in comparison with the compressive strength, concrete is practically never designed to withstand tensile stresses. It will usually be found to be more economical to use steel reinforcement than to depend upon the tensile strength of concrete.

The character of the workmanship and the materials used will greatly influence tensile strength, perhaps to an even greater extent than they affect compressive strength.

The series of tests enumerated in the following table were made by Prof. Mills upon specimens molded under ordinary field conditions. The compressive tests were made upon 6-inch cubes and the tensile tests upon prisms, 6 by 6 inches in cross-section.

(Note that the values of the ratio of tensile to compressive strength in the following table would have been somewhat lower had the specimens been tested in compression at the same age they were in tension.)

TENSILE AND COMPRESSIVE STRENGTH OF CONCRETE

Quality and mix.	Approx. age.		Compressive strength, lbs. per sq. in.	Tensile strength, lbs. per sq. in.	Ratio of tensile strength to Compressive strength.
	Tensile tests.	Compres. tests.			
1st Class Limestone 1 : 2 : 4	6 Mo.	1 Mo.	2206	278	
			2708	308	
			2500	253	
				306	
				264	
				257	
	Average....	....	2505	278	11.1%
1st Class Sandstone 1 : 2 : 4	6 Mo.	1 Mo.	1069	149	
			1375	142	
			1417	133	
			1722	178	
			2000	158	
			2139	128	
				153	
				150	
				161	
	Average....	....	1620	150	9.3%
2d Class Sandstone 1 : 2½ : 5	6 Mo.	2 Mo.	1028	121	
			1639	114	
			972	106	
			889	158	
			1042	114	
			2083	97	
			1472	179	
			1889	129	
			1639	139	
	Average....	....	1406	129	9.1%

76. Transverse Strength. The transverse strength of plain concrete is almost wholly dependent upon the tensile strength. Experiments show, however, that the modulus of rupture is considerably greater than the strength in tension. The following table represents the results of transverse strength tests made upon concrete beams 8 inches wide, by 10 inches deep, supported on spans varying from 3 to 8 feet. The materials used were Portland cement, a fairly clean bank sand of excellent granulometric composition, and crushed trap rock screened to remove all fragments under ¼ inch and over 1 inch in size.

The tests were made under the direction of Prof. Mills. Each result is the average of from six to eight separate tests made at an age of about three months.

TRANSVERSE STRENGTH OF PLAIN CONCRETE

Mix.	Modulus of rupture.
1 : 1½ : 3	470
1 : 2 : 4	389
1 : 3 : 6	216
1 : 4 : 8	112

77. Shearing Strength. The shearing strength of concrete is a most important property of the material, since it is the real determining factor in the compressive strength of short columns. The strength of concrete beams is also under certain conditions dependent upon the shearing strength of the material.

Since the angle of shear in concrete compression members must be slightly greater than 45°, we should expect the direct shearing strength to be slightly less than one-half the compressive strength. This theory has been well borne out by experiment as the data of the following table taken from tests made at the University of Illinois will show.

SHEARING STRENGTH OF CONCRETE

(EACH RESULT THE AVERAGE OF FROM 1 TO 17 TESTS)

Mix.	(S) Shearing strength, lbs. per sq. in.	(C) Compressive strength, lbs. per sq. in.	Ratio S/C.
1 : 2 : 4	1193	3210	0.37
1 : 2 : 4	1257	3210	0.39
Average	1225	3210	0.38
1 : 3 : 6	679	1230	0.55
1 : 3 : 6	729	1230	0.59
1 : 3 : 6	905	2428	0.37
1 : 3 : 6	968	1721	0.56
1 : 3 : 6	796	1230	0.65
1 : 3 : 6	692	1230	0.56
1 : 3 : 6	879	1230	0.71
1 : 3 : 6	1141	2428	0.47
1 : 3 : 6	910	1721	0.53
Average	856	1605	0.53

78. Elastic Properties. The elastic properties of concrete are of importance not only because of their bearing upon the deformation of concrete structures under load, but also because in the design of reinforced concrete it is necessary to know the relative stresses in the steel and the concrete under like distortions.

Fig. 39 presents typical stress-strain diagrams for short prisms of concrete in compression.

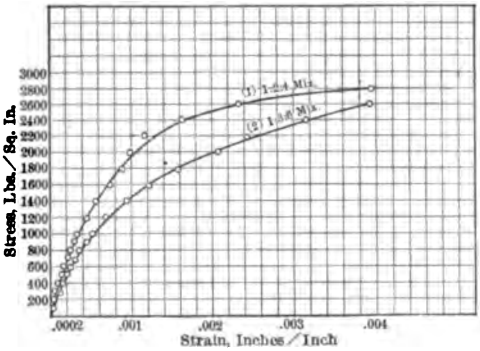

Fig. 39. — Stress-strain Diagram of Concrete in Compression. Age 3 Months.

Fig. 40 presents typical load-deflection diagrams for concrete beams under transverse loading. .

The elastic properties of concrete vary with the richness of the mixture and with the intensity of stress. They also vary with the age of the concrete.

Concrete is not perfectly elastic for any range of loading, an appreciable permanent set taking place for even very low loads, and the deformation is not proportional to the stress at any stage of the loading.

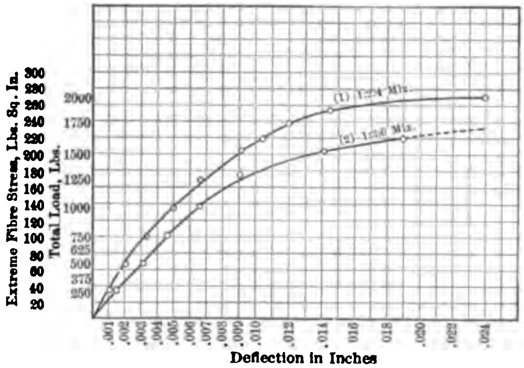

Fig. 40. — Transverse Tests of Concrete Beams. Beams 8″ Wide, 10″ Deep, 10′ Span. Age 1 Month. Single Concentrated load.

79. Modulus of Elasticity. Since the deformation of concrete is not proportional to the stress at any stage of the loading, the modulus of elasticity is not a constant for any appreciable range of stress, decreasing as the load increases. The modulus is higher for richer mixtures and increases with the age of the concrete.

The instantaneous value of the modulus may be computed on the basis of the slope of the chord drawn between two points on the stress-strain curve representing a change of stress not exceeding a few hundred pounds. The value of the modulus which is of importance in design and construction of concrete is that which corresponds to the working stress of the concrete. Assuming the concrete to be about one to two months old and the working stress not in excess of 500 pounds per square inch, the value of the modulus to be used will be about 2,000,000 to 2,500,000 pounds per square inch for 1:2:4 mix, and 1,500,000 to 2,000,000 pounds per square inch for the concrete of 1:3:6 mix.

80. Elastic Limit. As stated in Art. 78, concrete shows a permanent set under very low loads. There can be, therefore, no elastic limit in the true sense of the term. There appears to be a stress, however, below which repetition of the same load does not cause appreciable increase in set, while beyond this stress repetition of load causes increased set indefinitely, finally resulting in rupture far below the normal ultimate strength. For practical purposes, therefore, it is convenient to consider this stress as the elastic limit. Experiments made by Bach, Van Ornum, and others seem to place this stress at about 50 to 60 per cent of the ultimate strength.

81. Stress-strain Curves. The curves of Fig. 39 are typical stress-strain curves for concrete in compression. These curves have often been found to approximate closely to parabolas the axis of which is vertical, the origin being located at the point representing the ultimate strength.

This fact has been made the basis of some methods of concrete beam design wherein the variation in stress in the concrete is assumed to be parabolic from the neutral axis to the extreme fiber. This means that the design is really based upon the ultimate strength of the material. This method has been replaced to a great extent by methods which assume the stress-strain curve to be a straight line for stresses under the allowable working stress. The computations required are thus simplified, and the design is based upon safe working stresses instead of the ultimate strength of the material.

82. Coefficient of Expansion. The coefficient of expansion of 1:2:4 concrete has been determined by several investigators with considerable uniformity to be about 0.0000099 per degree Centigrade (0.0000055 per degree F.). This value differs so slightly from the coefficient of expansion of steel that there is little danger of failure of the bond of concrete and steel in reinforced concrete by reason of temperature changes.

83. Contraction and Expansion of Concrete. In addition to the volumetric changes due to temperature variation, concrete is subject to other volume changes caused, as in the case of mortars (Art. 73), by the chemical processes of setting and hardening or by variation in the moisture content. Experiments made to determine the expansion and contraction of concrete while hardening are not numerous, but they show conclusively that concrete hardened in air contracts, and concrete hardened in water expands, the amount of change in volume being dependent upon the richness of the mixture. Experiments made by

White (Art. 73) indicate that the expansion or contraction even in the case of old concrete, when alternately wet and dried, is far from being negligible. Pieces of concrete, presumably not leaner than 1 : 3 : 6 or richer than 1 : 2 : 4, sawn from a sidewalk after twenty years in service, showed an expansion of 0.05 and 0.06 per cent when placed in water, and the same contraction when subsequently allowed to dry in air.

If this concrete were restrained so that no volume change could take place, the resultant stresses introduced, considering the modulus of elasticity of the cement to be 2,000,000 pounds per square inch, would amount to from 1000 to 1200 pounds per square inch, a stress probably equal to at least half the ultimate strength if in compression, and far exceeding the ultimate strength if in tension.

84. Weight of Concrete. The weight of concrete is a factor in design, as it must be included in the dead load on any structure. The weight is dependent almost entirely upon the character of the aggregate and the density of the concrete. If the aggregate, both fine and coarse, is of well-graded stone and sand and the concrete deposited in a manner to insure the minimum of void space, the weight may run as high as 160 pounds per cubic foot, and for less carefully chosen materials or less perfectly executed work the weight may not exceed 140 pounds per cubic foot. For practical purposes of design it is customary to assume the weight of stone concrete to be 150 pounds per cubic foot. The weight of cinder concrete varies from 110 to 115 pounds per cubic foot.

85. Adhesion of Steel. The adhesion of concrete to steel is chiefly important in its bearing on the design of reinforced concrete. The bond strength is dependent principally upon the richness of the mix and the character of the surface of the steel. The following table based upon tests made at the University of Illinois gives representative values of the bond between concrete and steel rods.

ADHESION OF CONCRETE TO STEEL RODS

Mix.	Steel rods.			Adhesive strength, lbs. per sq. in.
	Kind.	Sise, inches.	Depth imbedded, inches.	
1 : 2 : 4	Plain round...........	$\frac{1}{2}$ and $\frac{5}{8}$	6	438
1 : 2 : 4	Plain round...........	$\frac{1}{2}$ and $\frac{5}{8}$	12	409
1 : 3 : $5\frac{1}{2}$	Plain round...........	$\frac{1}{2}$ and $\frac{5}{8}$	6	364
1 : 3 : $5\frac{1}{2}$	Plain round...........	$\frac{1}{2}$ and $\frac{5}{8}$	12	388
1 : 3 : $5\frac{1}{2}$	Cold rolled shafting....	1 and $\frac{1}{2}$	6	146
1 : 3 : $5\frac{1}{2}$	Mild steel flat.........	$\frac{3}{16} \times 1\frac{1}{2}$	6	125
1 : 3 : 6	Tool steel round.......	$\frac{3}{4}$	6	147

The adhesive strength of 1 : 2 : 4 concrete to plain round rods appears to be about 400 pounds per square inch. In situations where a higher bond strength is required it is customary to secure a mechanical bond by the use of some form of deformed bar.

86. Ratio E_c/E_s. The relative moduli of elasticity of concrete and steel determine the relative stresses in the two materials when the combined concrete and steel member is deformed a given amount. So long as the bond is not destroyed the ratio E_c/E_s fixes the relative stresses in the concrete and steel. E_c for concrete of 2000 pounds per square inch compressive strength is about 2,000,000 pounds per square inch, and for steel E_s is about 30,000,000 pounds per square inch. The value of the ratio E_c/E_s is, therefore, about 1/15.

87. Fire Resistant Properties of Concrete. Concrete as a fire resistant has been subjected to various experimental trials, but the best proof of its value so used lies in the experience afforded by many very severe fires wherein concrete well demonstrated its superiority over most other materials, which are used for fire protection.

The value of concrete as a protection for steel work in case of fire is due to several considerations. In the first place, concrete is in itself incombustible: second, its temperature coefficient is practically the same as that of steel, thus giving it an advantage over materials like terra cotta, which expands much more rapidly than does steel, and hence tends to fail by reason of the destruction of the bond caused by unequal expansion; third, the rate of heat conductivity of concrete is very low, due in part to its porosity and consequent air content, and in part to the dehydration of the water of chemical combination, the volatilization of which absorbs heat. This latter action increases the porosity, and hence the conductivity of the concrete which has suffered dehydration is still further lowered, and the penetration of the dehydrating action proceeds very slowly.

The concrete which thus becomes dehydrated is seriously injured, but the effect is seldom appreciable to a depth of more than a fraction of an inch, except in very hot and long-burning fires. Concrete called "cinder concrete," in which the usual coarse stone aggregate has been replaced by cinders, has been found quite as effective a fire resistant as is stone concrete.

In general it is considered that a covering of concrete over steel work, 2 inches in thickness, is sufficient to effectually protect the steel against temperatures sufficiently high to cause warping and twisting, with consequent failure of the structure.

88. Protection of Steel from Corrosion. Experience gained at the time of the demolition of reinforced concrete structures after years of exposure in damp situations, and carefully conducted experiments, as well, have shown that concrete forms a most effective preventive of the corrosion of steel imbedded therein. Particularly is this true if the concrete be mixed sufficiently wet so that the steel is completely covered by a wash of thin grout.

Experiments made by Professor Charles L. Norton for the Insurance Engineering Station in Boston led to the following conclusions:

"Neat Portland cement, even in thin layers, is an effective preventive of rusting.

"Concretes, to be effective in preventing rust, must be dense and without voids or cracks. They should be mixed quite wet where applied to the metal.

"The corrosion found in cinder concrete is mainly due to the iron oxide, or rust, in the cinders and not to the sulphur.

"Cinder concrete, if free from voids and well rammed when wet, is about as effective as stone concrete in protecting steel."

CHAPTER II

CONCRETE

89. Concrete as a Structural Material. All of the masonry materials heretofore discussed (plasters, limes, and cements), have been strictly cementing materials. Alone, they are not used as masonry, but are used in combination with such non-cementing masonry materials as brick, stone, terra cotta, etc., or are used as a plaster coat in walls.

Concrete, considered as a cementing material, is used alone to form bulk masonry. If we consider the constituent materials from which concrete is made, however, instead of considering concrete masonry as one material, we find that we have to deal with a class of masonry which is made up of a large bulk of non-cementing materials bound together by a comparatively small amount of cementing material, just as is the case with stone or brick masonry. The distinction lies, however, in the fact that in concrete the non-cementing material is in a comparatively finely divided state, and is incorporated in a mix with the cementing material prior to placing on the work. In stone or brick masonry, on the other hand, the non-cementing material is brought upon the work in the shape of conveniently sized units with which the structure is built up, cementing material being used only as beds and joints to bind the stone or brick together.

Concrete may be strengthened or reinforced by the use of steel. This makes its use possible in situations where tensile stresses are encountered, whereas stone and brick masonry may be depended upon to withstand compressive stresses alone.

The subject of reinforced concrete is so complex, the problems encountered in design and construction are so peculiar to this class of construction alone, and the bibliography of the subject is already so extensive, that the discussion of concrete in this chapter will not be made to include reinforced concrete.

CONCRETE MATERIALS

THE CEMENT

90. Selection of Cement. Most engineers specify the use of Portland cement for all classes of concrete work. Any cement used should be accepted under standard specifications such as those of the American

Society for Testing Materials and, except on the least important work, samples from each shipment should be subjected to the standard tests.

91. Storage of Cement. After delivery on the work the cement should be carefully stored in weather-tight, but not air-tight, buildings, the floors of which are raised from the ground. The storing should be done in such a manner as to permit of easy access for inspection and identification of each shipment.

92. Inspection and Testing. Each shipment of cement should be inspected by a competent inspector whose duty it is to select a sample for tests. The sample should be a fair average of a bag or barrel and, if conditions permit, about 1 barrel in every 10 should be sampled. Usually tests are made on a mixture of the individual samples, but in some cases on important work the individual samples are tested separately.

Sand for Concrete Aggregate

93. Granulometric Composition. In general, the discussion of sands for mortars included in Chapter I applies with equal force to the consideration of sands for concrete. Investigations have shown that the sand should be for the most part coarse, rather than fine. A sand showing proper gradation in size from fairly coarse to fairly fine is preferable to either a uniformly coarse or a uniformly fine sand. A rough empirical rule often used requires that not more than 50 per cent of the sand shall pass a 30-mesh sieve and not more than 10 per cent shall pass a 100-mesh sieve.

94. Foreign Matter in Sand. It has been shown in Chapter I that the injurious effect of foreign matter in sand is dependent upon many factors. If the silt contains more than 10 per cent of organic matter, the latter constituting as much as one-tenth of 1 per cent of the sand, an appreciable injury results. Clay, if finely divided and uniformly distributed throughout the sand, appears to have little effect unless present in large percentages, perhaps 10 per cent or more. Mica is injurious even in very small percentages.

It is important, therefore, that the sand used on concrete work should be subjected to careful examination and tested systematically. It is not sufficient to specify that the sand be "clean and sharp" and accept it upon the basis of a casual inspection made by taking a bit between the fingers to establish its grittiness, and determining its cleanliness by the amount of discoloration produced by rubbing it in the palm of the hand. Presence of harmful matter can be determined by ignition of the silt, by a water wash test of the silt, or by the wash test with sodium hydroxide. A strength test gives the most reliable result. It is not necessary that the sand should be sharp.

BROKEN STONE OR GRAVEL AGGREGATE

95. Gravel vs. Broken Stone. Either class of coarse aggregate may be perfectly satisfactory, and neither can be said to be wholly superior to the other. If the consistency of the concrete is such as to constitute a rather dry mix, more tamping is necessary to obtain a dense concrete with broken stone than is the case with gravel consisting of smoother and more rounded particles.

Gravel usually has a smaller percentage of voids than has broken stone, and therefore a compact concrete may be secured with a somewhat smaller amount of mortar than would be required for broken stone.

On the other hand, if properly tamped, the broken stone will to some extent interlock, forming a dense and strong concrete, the same effect being possible with a well-puddled wet mix. Also, the rough surface of the broken stone usually results in developing a greater adhesive strength or bond between the stone and the mortar. This latter consideration cannot be taken to be universally applicable, however, for the adhesion of cement to stone is not wholly a matter of roughness or smoothness.

96. Size and Shape of Fragments of Stone. All material under ¼ inch or even ⅜ inch should be removed from either crushed stone or gravel, this fine part being in some cases suitable for use as sand. The maximum size of coarse aggregate allowable depends upon the character of the work on which the concrete is used. Usually this limit is such a size as will pass a 2½-inch ring. For massive concrete, however, the size may be such as will pass a 3-inch ring, and for reinforced concrete a size to pass a 1-inch ring may be required.

From the standpoint of minimum void space rounded stones are more desirable than irregular rough fragments; from the standpoint of ability to bond with the mortar they are deficient, however, so that in general the shape of the particles will be found to be much less important than the size and the hardness of the stones.

THE PROPORTIONING OF CONCRETE

97. Importance of Proper Proportioning. Upon important work, particularly if of large extent, a thorough study of the materials and the proper relative proportions will often effect better results with a saving in cost. The cement is always the most expensive ingredient, and therefore if it is possible to reduce the proportion of cement used by adjusting the proportions of the aggregates in such a manner as to produce a leaner mixture of equal or greater density and strength, economy is thereby effected.

98. Theory of Proper Proportioning. The theories of proportioning first accepted were based on the assumption that greatest strength and imperviousness were obtained by the mixture of maximum density. The methods of proportioning with this end in view are known as proportioning by the method of:

Arbitrary Assignment,
Voids,
Maximum Density,
Mechanical Analysis.

The more recent theories have not emphasized the maximum density, in fact they have even denied that it is necessary. The two methods which have caused the widest discussion are the methods of:

Water Ratio and Fineness Modulus,
Surface Areas.

99. Proportions by Arbitrary Assignment. For concrete of maximum density the voids in the stone aggregate should be filled with mortar, where in turn the cement has filled the voids in the sand. The voids in practice are not completely filled as the excess of water used and the entraining of air bubbles during mixing leaves voids. The percentage of voids in natural gravel usually runs from about 30 to about 35 per cent, while in crushed stone the percentage will in general vary all the way from 30 to 45 per cent, depending upon the shape and gradation in size of the particles. Arbitrary assignment commonly calls for a volume of sand equal to half the volume of stone. The amount of cement used depends upon the strength desired for the concrete and upon its use.

It is customary to state concrete proportions by volume, giving the number of parts of sand and stone to one of cement. It is hardly possible to state arbitrarily the proportions used in practice for concrete in any particular situation. The following division is given, however, as fairly representative of present conservative practice:

1 : 1½ : 3 — a rich mixture used for columns and other structural parts subjected to high stresses or requiring especial water-tightness.

1 : 2 : 4 — a standard mixture used for reinforced floors, beams, columns, arches, engine and machine foundations where vibration occurs, sewers, conduits, etc.

1 : 2½ : 5 — a medium mixture used for floors on the ground, ordinary machine foundations, retaining walls, abutments, piers, thin foundation walls, building walls, sidewalks, etc.

1 : 3 : 6 — a lean mixture for massive concrete, heavy walls, large foundations under steady load, stone masonry backing or filling, etc.

1 : 4 : 8 — a very lean mixture used only on unimportant work in very large masses.

100. Proportions by Voids. The mix can more accurately be determined for any given aggregates by ascertaining the actual voids in the stone or sand. A representative sample of stone is commonly taken in a large bucket or container. The voids are determined by finding the volume of water required to fill the air spaces in the given volume of stone.

$$V = \frac{100\,W}{T}$$

where V = per cent of voids,
W = volume of water in voids,
T = total volume of container (aggregate plus voids).

The percentage of voids varies with the compactness of the sample. If a stone is shaken the voids are much reduced. The voids in stone are usually determined in the unshaken condition as approaching more nearly the actual concreting conditions.

The sand aggregate is more difficult to deal with in void determinations as it has much finer particles. The compactness of the sample makes a great difference in results, also if the finer grains are damp the material will increase in volume on handling. It is customary to determine the voids in sand as dry material, well shaken, and the determination is better made by dropping the sand into a given volume of water.

$$V = \frac{100\,(T - W)}{T}$$

where V = per cent of voids,
W = volume of water displaced by the sand,
T = total volume of container to the sand level.

If the aggregate is composed of particles of the same type of rock and the specific gravity is known, the voids may be computed directly.

$$V = 100\left(1 - \frac{W}{62.4\,S}\right)$$

where V = per cent of voids,
S = specific gravity of the particles of the aggregate,
W = weight per cubic foot of dry aggregate.

To proportion a mix the voids in the stone are determined and that volume of mortar provided. The voids in the sand may also be found and the proper amount of cement supplied. Many engineers, however, prefer to adjust the mortar rates according to the strength desired and then proportion by voids to fix the mortar-stone ratio. Long experience has shown that it is necessary to provide 5 to 10 per cent more mortar than called for by a void determination on the stone as the sand particles separate many stones and create new voids.

TABLE I. AVERAGE SPECIFIC GRAVITY OF VARIOUS AGGREGATES *

Material.	Specific gravity.	Weight of a solid cubic foot of rock, pounds.
Sand	2.65	165
Gravel	2.66	165
Conglomerate	2.6	162
Granite	2.7	168
Limestone	2.6	162
Trap	2.9	180
Slate	2.7	168
Sandstone	2.4	150
Cinders (bituminous)	1.5	95

* From "Concrete — Plain and Reinforced," Taylor and Thompson.

Void determinations have proved that: — An aggregate whose particles are all one size will have approximately the same per cent of voids as any other equal sized aggregate, whatever the particle diameter may be.

The largest per cent of voids for any aggregate occurs with particles of uniform size; the smallest per cent of voids occurs with a mixture of sizes such that the voids of each size are filled with the largest particles possible. Therefore a mixture of stone and sand is more dense than sand alone.

Aggregates with round particles, such as gravel, contain less voids than aggregates with angular particles, such as crushed stone, even though they are screened on identical sieves.

The addition of water to dry sand increases the voids. The largest per cent of voids for bank sands occurs with 5 to 8 per cent of water. Ordinary sands as they come from the bank contain 2 to 4 per cent of water.

Proportioning by voids indicates the maximum density of the individual aggregate. The necessity of adding 5 to 10 per cent additional material over the void determination prevents this from being a precise method of proportioning.

101. Proportions by Maximum Density. The concrete of maximum density can be determined by trial mixes. Some constant ratio of cement to aggregate is adopted. The relative percentage of sand to stone is varied, all volumes being carefully measured. Each mix is rammed into a container under uniform conditions and the resultant height measured. Variations of the volume of the rammed concrete indicate the density change. As the per cent of sand to stone is increased towards 50 per cent a point of maximum density is reached. Up to this point there has been too much mortar and a separation thereby of the stone particles (Figs.

41 and 42), beyond this point there is not enough mortar and the voids are increased. The strength and density curves (Fig. 43) show that maximum strength and maximum density for this aggregate are practically identical.

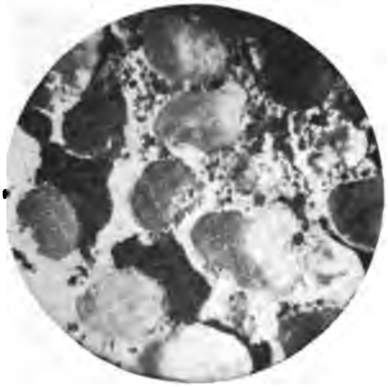

Fig. 41. — Photomicrograph of Cement-Ottawa Sand Mortar, showing Small Voids.

Fig. 42. — Photomicrograph of Cement-Ottawa Sand Mortar, showing Large Voids.

Proportioning by maximum density has the advantage compared with the method of voids of dealing with the materials mixed under field conditions. It gives immediate results if only one sand and stone are considered; but, if there are available a number of stones, either screened or "run of bank," the number of mixes required would be large in order to determine what sand or stone or combination of stones could be used to best advantage.

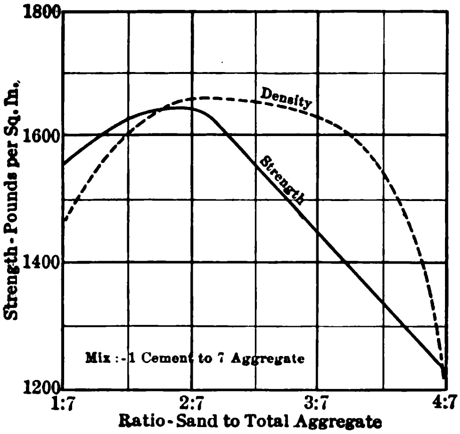

Fig. 43. — Density and Strength Relation.

102. Proportions by Mechanical Analysis. On important work mechanical analysis of the aggregate is desirable since it affords a basis for determining the best proportions to be used with given materials, or for determining what sized material should be added to the aggregate to make it more satisfactory for use in a concrete of given proportions. The least dense mixture of aggregate is made up of particles, all of one size, the densest mix of particles of graded sizes. A coarse aggregate of one size is preferable to a fine one, since there is less surface area to be coated with the cement. Fine aggregates are less dense and require more cement and water to coat their particle surfaces. This additional amount of paste still further reduces the density, and gives an additional cost.

The availability of an aggregate for a concrete mixture may be determined by a mechanical analysis of its particle sizes. This sieve analysis is obtained by screening a representative sample of the dry aggregate through a series of sieves with decreasing sizes of openings. The cumulative percentages held (or passing) each screen are an indication of the grading of the material. This is shown by plotting the cumulative per cent as an ordinate against the diameter of the particle as given by the screen opening as an abscissa. (Fig. 44.) M. Feret and others have made careful study of the results of artificial mixes of aggregates. They proved, if aggregates were screened into three sizes, coarse, medium and fine, that the combination with greatest density was a mixture of 73 per cent coarse and 27 per cent fine with no medium at all. Greatest strength was given by nearly the same proportions, being 80 per cent coarse and 20 per cent fine aggregate. Stone of one size can be combined with finer stone or with a sand in accordance with these results.

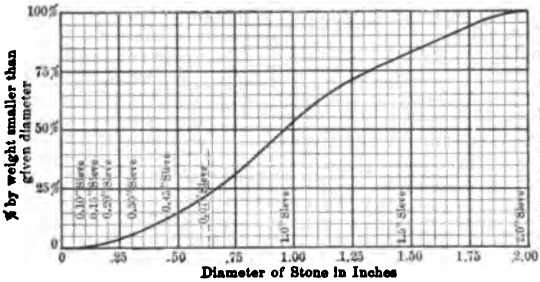

FIG. 44. — Typical Mechanical Analysis of Gravel.

Many "run of the bank" aggregates do contain medium size material, which cannot be conveniently screened out. The densest mixture of such a material gives a gradation plot which appears to be a regular curve.

Mr. William B. Fuller determined by strength, density and permeability tests such a curve for the best grading of aggregate to be approximately a parabola (Fig. 45). For practical use he assumed the ideal grading to be a straight line in the coarse and medium sizes and an ellipse in the fine sizes. To proportion a dense mix the sand and stones are screened and their gradings plotted. The per cent of each to use is then determined so that their combined grading plot will most nearly coincide with the ideal curve. It is possible to determine readily what sand and stone or stones to use, and the proportions of each. The cement ratio is usually assumed, either as the ratio of cement to aggregate or as the mortar ratio of cement to sand. The results do not check M. Feret's conclusions, since he dealt with screened material, which could be artificially graded, leaving out certain sizes, while Fuller's curve applies to material containing all sizes, or to mixtures of several sizes of screened materials.

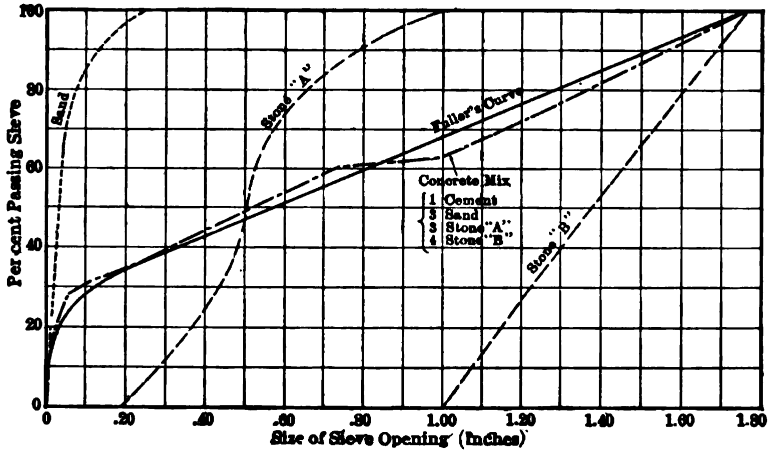

FIG. 45.

·103. Effect of Water. Proportioning by voids or by mechanical analysis aims to give the densest mix and to indicate the best materials to use out of many available. The problem frequently arises, however, of determining the amount of cement to use to give a requisite strength with only one set of aggregates. The more recent methods of proportioning attack the problem from this point of view. They endeavor to establish relations between all sorts of aggregates so that the cement ratios can be predicted. The economical aggregate would then be easily determined.

The methods of proportioning previously discussed have not directly considered the effect of the amount of water used in the mix. This amount should be considered carefully. Water reacts with the cement particles causing chemical changes that result in the formation of the paste that binds the sand and stone particles together. If there is not enough water the reaction with the cement will not be complete and low strength results. If there is too much water, this paste will not be strong. As the cement sets crystals form which interlace and increase the strength; crystallization can only take place from saturated or supersaturated solutions. A moderate excess of water may affect the strength as much as 40 per cent.

In addition to starting the chemical reactions, the water wets the surfaces of the sand and stone particles filling all cracks and minute irregularities with the paste that binds all together. If there is not enough water, poor binding surfaces are the result. If there is too much, the excess will evaporate leaving holes which weaken the bond and leave the concrete permeable.

It has been claimed that excess of water acts as a lubricant in the transporting of the aggregate to the final place in the forms. It certainly tends toward the separation of the paste from the sand and especially from the stone. As the cement hydrates, certain amounts of hydrated lime form, which aid to lubricate the flow of the concrete and also aid to bind it together. Therefore excess water is not necessary.

104. Proportioning by Water Ratio. Prof. Duff A. Abrams has advocated the use of a method of proportioning concrete which is based on the water used to make the mix. The term "water ratio," as used by him, is the ratio of the volume of water to the volume of the cement. His tests tend to prove that the strongest concrete is that which requires the least water ratio to give a required consistency of mix.

Thus, if a certain aggregate were used, it would require a definite amount of water to wet the particle surfaces. When mixes are made with this aggregate and increasing amounts of cement, the water required for aggregate and cement will give a less water ratio. This agrees with the usual statement that richer mixes of the same aggregate give greater strengths. Again, if the ratio of cement to aggregate is kept the same, but aggregates are used of such grading that less water is needed to wet the particle surfaces, the water ratio is decreased. Aggregates proportioned by the methods of voids, maximum density, or mechanical analysis tend to produce this low water ratio. It is only the water that enters into chemical action with the cement that is essential.

Prof. Abram's method may seem only to be a statement from another point of view of the previous theories; but he also quotes tests to prove that the grading giving greatest strength is not that of maximum density, but a coarser grading. His tests show that aggregates of considerable difference in grading and in surface areas of the particles may give the same strength. The tests have been summarized in a plot (Fig. 46) which gives the relation between the compressive strength of 6 inch diameter concrete cylinders, 12 inches high, at an age of 28 days, and the water ratio of these concretes. The curve obeys the equation $S = \frac{A}{B^x}$, where S = the compressive strength of the concrete in lbs. per sq. in., A and B are constants, x = the water ratio.

For Fig. 46 the equation is $S = \frac{14{,}000}{7^x}$. The aggregate does not appear in this equation, but it does exert its influence through the water ratio.

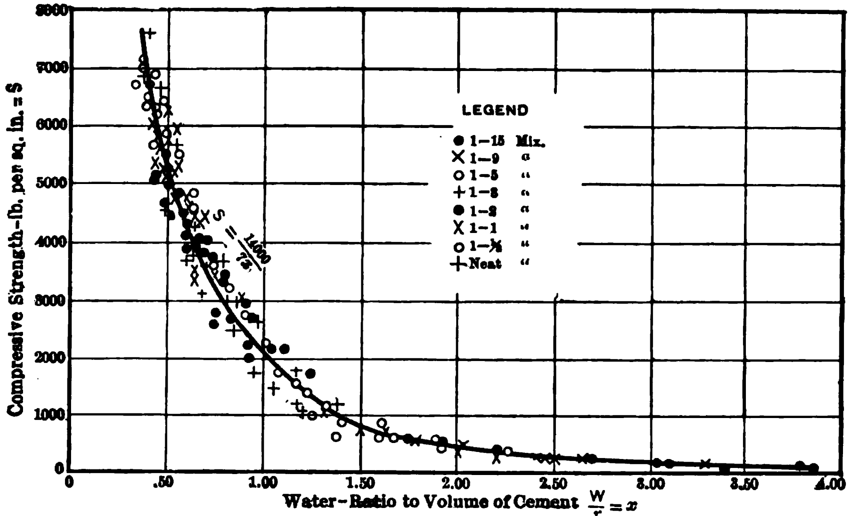

FIG. 46.

The aggregate is studied by means of mechanical analysis, using the Tyler standard series of sieves for the 100, 48, 28, 14, 8 and 4 mesh and

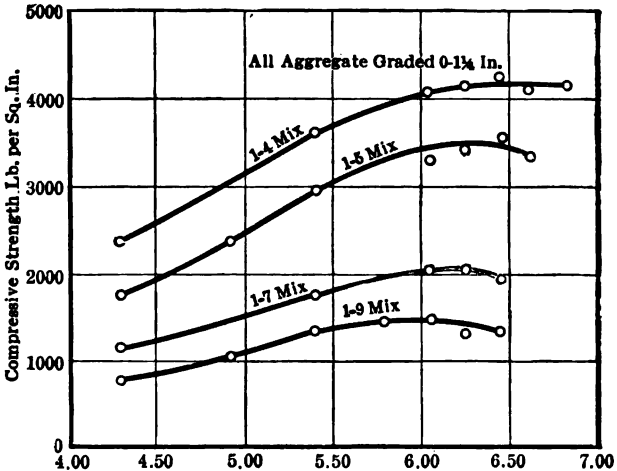

FIG. 47. — Relation between Fineness Modulus of Aggregate and Strength of Concrete.

the ⅜, ¾, and 1½ inch sizes. The per cents of the aggregate held on each of the nine screens are added together to give a constant which is known as the "fineness modulus." This fineness modulus is a measure of the grading of the material; a very fine sand giving a modulus as low as 1.25, while coarse stone could be as high as 8.00. The same amount of water is needed to wet the aggregate, if the material has a given fineness modulus, whether it be sand, stone, or a mixture of the two. When the ratio of cement to aggregate is kept constant, the strength increases with the fineness modulus of the aggregate to a maximum. (Fig. 47.) Fineness moduli above this value mean that the material is too coarse for the cement paste to fill the voids.

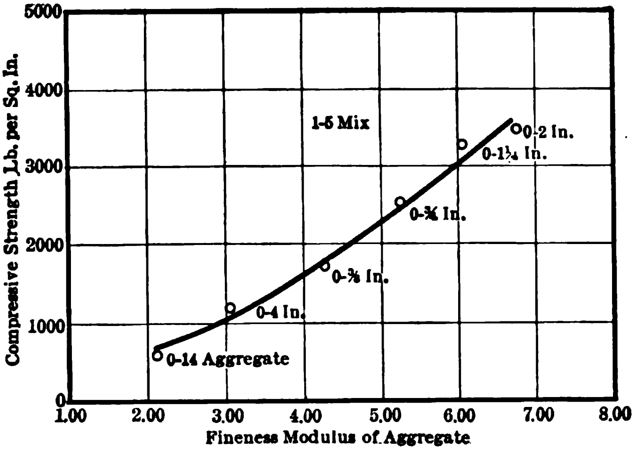

FIG. 48. — Relation between Fineness Modulus of Aggregate and Strength of Concrete.

There is, then, a certain maximum fineness modulus for each mix and aggregate size beyond which value the aggregate should not be used. The maximum is higher for rich mixes than for lean mixes. When aggregates are used where the largest size varies, the same cement-aggregate ratio being used, the strength steadily increases with the fineness modulus, no maximum being reached. (Fig. 48.)

The water used in the mix depends on the cement content, on the aggregate used and on the consistency of the mix. Prof. Abrams has considered all these factors in the simplified equations for the water content

$$(1) \qquad x = R\left[\frac{3}{2}p + \left(0.22 - \frac{m}{42}\right)n\right] + (a - c)\,n,$$

where

x = the water ratio.

R = the relative consistency of the concrete (ratio by volume), a consistency of 1.00 being produced by such an amount of water that the concrete will slump ½ inch to 1 inch upon removal of the metal mold of a 6″ × 12″ specimen.

p = the normal consistency of the cement (ratio by weight).
m = the fineness modulus of the aggregate.
n = the mix. The ratio of aggregate volume to the cement volume.
a = the absorption of the dry aggregate (ratio by volume).
c = the moisture contained in aggregate (ratio by volume).

To design a mix, the water ratio for the desired strength is determined from Fig. 46. Substituting in equation (1), the values of x, R, p, a and c which are known and assuming a mix n, the aggregate fineness modulus can be solved. Knowing the fineness modulus of the sand and stone, it is possible to figure the ratio of sand to stone to give the required aggregate modulus. It is desirable to use the leanest mix possible and the mix n can be varied until the modulus m approaches the maximum allowable value for that mix. The strengths used in Prof. Abram's plots are obtained on laboratory mixed concretes which are stronger than the corresponding mixes in the field. Allowance for this fact should be made, when using this proportioning method.

105. Proportioning by Surface Areas. Mr. L. N. Edwards has advocated the proportioning of concrete mixtures by the consideration of the surface areas of the aggregate, which must be coated by the cement paste. He recommends that concretes be proportioned as the ratio of 1 gram of cement to a given number of square inches of surface area of aggregate. Such a method relies on the fact, shown by his tests, that all mixes of the same ratio (as 1 gram of cement to 10 sq. in. of aggregate) give the same strength. Concrete of a required strength can be proportioned from any aggregate, the weight of cement used in a cubic foot of concrete varying with the aggregate as in other methods. A fine sand or stone having a large surface area for the same volume of material would require much more cement. Mr. Edwards determined representative data for sands and stones in his locality (Toronto, Canada), for the areas of different sizes of material.

Mr. Edwards' published tests have been largely made on mortars rather than concretes but the method of solution is the same. The sands were separated into sizes by screening through the 4, 8, 10, 20, 30, 40, 50, 80, and 100 mesh sieves, therefore direct comparison cannot be made with Prof. Abrams' "fineness modulus." The number of particles per gram weight was determined for each size. Assuming sand particles to be spherical the surface area per gram was figured. Table II and Fig. 49 show the results for the sands examined.

TABLE II. — VOLUME AND SURFACE AREA OF SAND

Sieve passed and retained on.	Number of particles per gram.	Average volume per particle, cu. in.	Average diameter per particle, in.	Surface area per particle, sq. in.	Surface area per gram, sq. in.
P 4 –R 8	14	0.001 66	0.146 95	0.0678	0.9492
P 8 –R 10	55	0.000 4226	0.093 1058	0.027 2335	1.4978
P 10–R 20	350	0.000 066 45	0.050 2534	0.007 9338	2.7778
P 20–R 30	1 500	0.000 015 49	0.030 928	0.003 0055	4.5083
P 30–R 40	4 800	0.000 004 842	0.020 9893	0.001 3841	6.6437
P 40–R 50	16 000	0.000 001 452	0.014 0818	0.000 6201	9.9216
P 50–R 80	40 000	0.000 000 5815	0.010 3568	0.000 336 913	13.4765
P 80–R 100	99 000	0.000 000 2348	0.007 6538	0.000 188 325	18.6442
Standard Ottawa	1 323	0.000 017 57	0.032 2545	0.003 268 38	4.3241

For the concrete aggregates, crushed stone is angular while gravel appears more nearly spherical. Therefore the crushed stone was assumed to be one-third cubical and two-thirds parallelepipedal shapes, and the gravel particles were called spherical. The stones were screened on the ¼, ½, ¾, 1, 1½ and 2 inch sieves. Tables III and IV give the number of particles in 100 pounds and the surface area in square feet per 100 pounds for broken stone and for gravel. Fig. 50 shows the graph of these results.

To proportion a concrete the ratio of cement to surface area is determined to give the required strength by the result of tests. Fig. 51 shows the results of such a series of tests for pit-run gravel by Mr. R. B. Young.

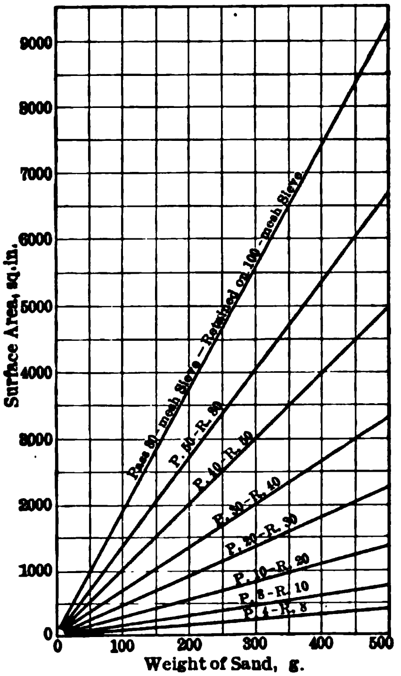

Fig. 49. — Surface Areas Corresponding to Various Weights of Sand.

TABLE III. — VOLUME AND SURFACE AREA OF BROKEN STONE AGGREGATE

Screen passed and retained on.	Number of particles in 100 lb.	Average volume per particle, cu. in.	Surface area per particle, sq. in.	Surface area per 100 lb., sq. ft.
P 2 –R 1½	670	1.553	8.7047	40.5
P 1½–R 1	1 680	0.636	4.9261	57.47
P 1 –R ¾	5 680	0.1811	2.1139	83.38
P ¾–R ½	14 900	0.0692	1.1943	123.58
P ½–P ¼	43 820	0.0236	0.5339	162.47

TABLE IV. — VOLUME AND SURFACE AREA OF SCREENED GRAVEL

Screen passed and retained on.	Number of particles in 100 lb.	Average volume per particle, cu. in.	Average diameter per particle, in.	Surface area per particle, sq. in.	Surface area per 100 lb., sq. ft.
P 2 –R 1½	430	2.4289	1.6678	8.7383	26.09
P 1½–R 1	1 090	0.9509	1.2201	4.6764	35.39
P 1 –R ¾	3 830	0.2694	0.8013	2.0330	54.00
P ¾–R ½	10 030	0.1020	0.5797	1.0557	73.54
P ½–R ¼	37 330	0.0276	0.3753	0.4425	114.71

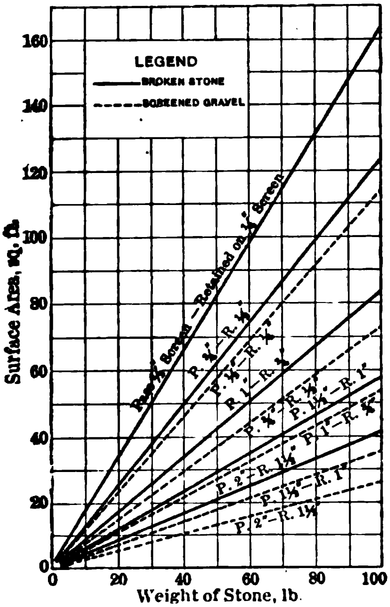

FIG. 50. — Surface Area for Stone.

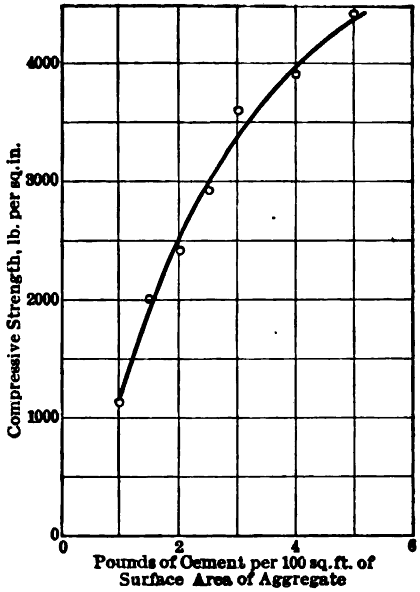

FIG. 51. — Cement-Strength Relation for Concretes.

The aggregate is screened and the surface area figured per 100-pound weight, and the weight of cement per 100 pounds of aggregate obtained. It is realized that the water used is a potent factor. Normal consistency for mortars is given by an amount of water obtained as follows:

$$\text{water (c.c.)} = \left(\begin{array}{c}\text{Weight of cement } (g) \times \text{ percentage required} \\ \text{to produce ``normal consistency'' paste}\end{array}\right) + \frac{\text{total surface area of sand (sq. in.)}}{210}$$

For concretes Mr. Young used a normal consistency given by Fig. 52. If this water ratio did not give the correct working results, it was changed but the cement ratio was increased as the water was increased. When one aggregate is available, this method gives immediate results. If several sands and stones can be used, the most economical aggregate is that which has the least surface area for a given volume; the amount of cement required being then a minimum, though the cement ratio is not changed.

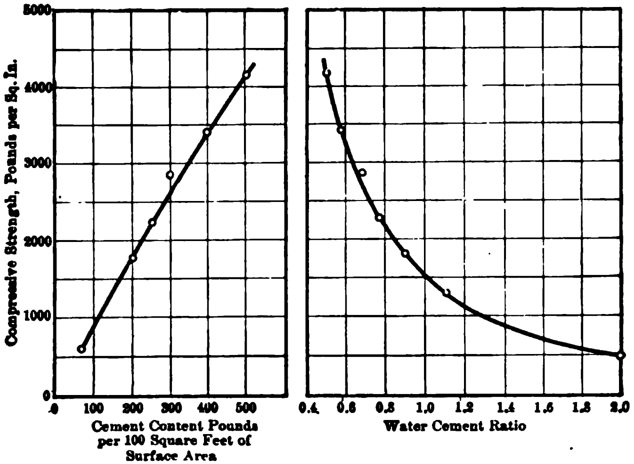

FIG. 52. — Curves establishing Relation between Compressive Strength, Water-Cement Ratio and Cement Content at Normal Consistency.

106. Summary. The method of proportioning to use depends upon the quality of concrete to be made. Small amounts of concrete of a lean mix can be given arbitrary assignment of mix. Mixes determined by voids or by maximum density by trial can be made on the job with fairly good results. The proportions of concrete must be determined with care to give high strength for buildings, or strength and water-tightness in dams and tanks, or to resist wear in roads.

The best aggregate can be found by some form of mechanical analysis. Prof. Abram's studies give information in regard to water content. His method or the more direct relation of surface areas enables one to estimate the cement content and the probable strength.

MIXING CONCRETE

107. Ingredients Required per Cubic Yard of Cement. Cement is usually bought and measured by the barrel, the weight of the barrel being 376 pounds net and the volume about 4 cubic feet. Sand and stone are bought and measured by the cubic yard, so that it will usually be convenient to determine the number of cubic yards of sand and stone or gravel for each barrel of cement in a concrete of a given mix.

The following rule will be found to be sufficiently accurate for the purpose of making preliminary estimates of quantities:

Let c = the number of parts of cement;
s = the number of parts of sand;
g = the number of parts of stone or gravel.

Then $\frac{10.3}{c+s+g} = P$ = barrels of cement per cubic yard of concrete in place;
and $P \times s \times 4/27$ = cubic yards of sand per cubic yard of concrete;
$P \times g \times 4/27$ = cubic yards of stone per cubic yard of concrete.

This rule has been devised by experimental determination of the constant 10.3. It will give fairly accurate results with all classes of materials except with rather fine gravel, or stone which shows a very excellent gradation in size of fragments. In this event the quantities of each of the ingredients other than stone, as determined by the rule, will be found to be about 10 per cent in excess of actual requirements.

108. Hand vs. Machine Mixing. Good concrete may be either hand or machine mixed, the choice depending largely upon the quantity required, and the consequent relative costs of the two methods. For all except the smallest work machine mixing will be less expensive than hand mixing, and for this reason, as well as the greater likelihood of obtaining uniformly well-mixed concrete of uniform consistency, machine mixing is generally preferred. Hand mixing is apt to be slighted because of the heavy labor demanded.

109. Method of Mixing by Hand. Hand mixing should be done upon a water-tight platform about 10 feet wide by 15 feet long. The measured quantity of sand having been spread over the surface of the mixing platform, the cement is spread evenly over the sand and the two mixed thoroughly dry, after which the required amount of water and stone may be added and the mass turned back and forth from one side of the board to the other until the mass is homogeneous in appearance and color. From three to five turnings are required to mix the concrete thoroughly.

110. Mixing Machines and Machine Mixing. Concrete-mixing machines are of two general classes — batch mixers and continuous mixers. In using the batch mixer, the materials are measured separately and charged into the machine in quantities sufficient to make a batch suited to the capacity of the machine. The required amount of water is added, and the mass is mixed and then completely discharged, after which the machine is recharged. In the continuous mixers the materials are delivered gradually to the machine, either already combined in the correct proportions or the rate of feed of each material may be regulated to produce the required mix as nearly as possible. Water is added as the materials pass slowly through the length of the mixer and the mass is discharged continuously from the lower end. Continuous mixers do not generally produce a concrete so thoroughly mixed or of as uniform a consistency as is obtained with the use of batch mixers. Specifications for important work very often stipulate that batch mixers be used.

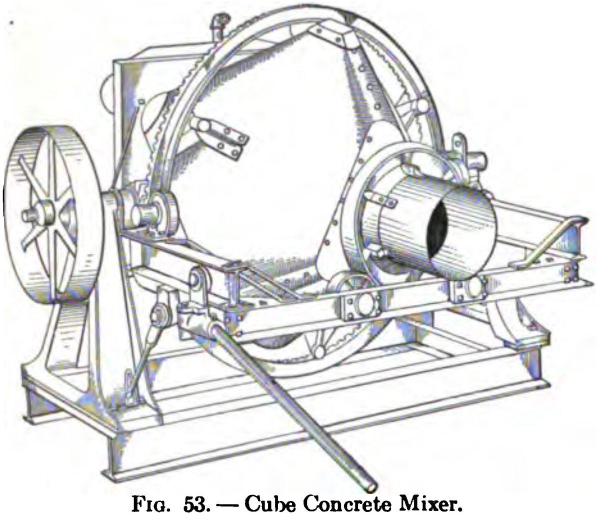

FIG. 53. — Cube Concrete Mixer.

Most concrete mixers consist of a rotating chamber into which the materials are charged and mixed with a complicated motion, due either to the shape of the mixer chamber or to the action of baffle plates placed on the inside walls of the mixing chamber. The cube mixer (Fig. 53) requires no baffle plates because of its peculiar shape and manner of mounting. The drum-shaped mixer (Fig. 54) is provided with baffle plates of various kinds. One arrangement is shown by Fig. 55.

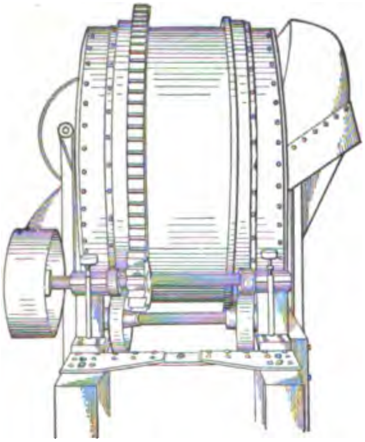

FIG. 54. — Drum Type Concrete Mixer.

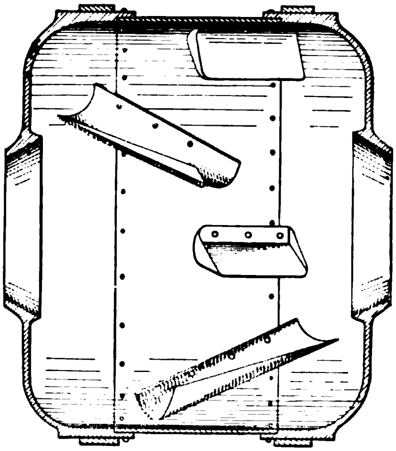

FIG. 55. — Mixing Chamber of Drum Type Concrete Mixer.

A machine known as the Cement Gun is also used to deposit cement mortars in the form of "Gunite." The dry mix of cement and sand is introduced into the upper chamber (Fig. 56) of the gun through a cone valve. Compressed air equalizes the pressure in this chamber with that in the lower chamber, whereupon a second cone valve admits the mixture to the lower chamber. The material is fed continuously from this chamber through a hose to the place of deposition. As it leaves the hose through a specially designed nozzle, water is added. The wet mix strikes the surface on which the mortar is deposited with great force, the surplus water is thrown off, and a very dense mortar is formed which is stronger than mortars placed by hand.

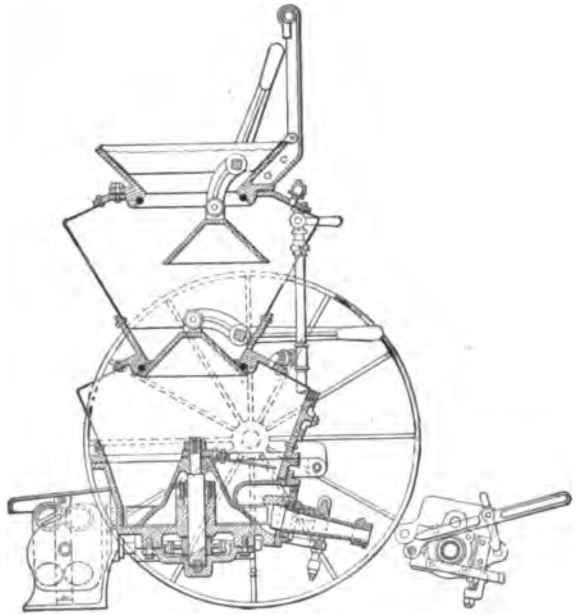

Fig. 56. — Cement Gun.

Deposition of Concrete

111. Timber Forms. The investment in materials and the cost of labor in placing and removing forms represents quite a large per cent of the total cost of concrete work. It is evident, therefore, that the correct design and construction of forms is a very important feature of the work. Forms must be substantially built, so thoroughly braced and wired that the finished concrete shall conform to the designed dimensions and contours, and made tight to prevent the leakage of cement-charged water.

The cheaper grades of lumber are generally used. Green timber is preferable to seasoned timber, since it is less apt to be affected by the water in the concrete. Better grades of lumber are used when a particularly smooth finish is desired or where forms are used repeatedly. Oiling of the forms is beneficial, and plank planed on one side is practically essential. Forms should always be wetted just prior to the deposition of the concrete.

112. Transportation and Deposition in Forms. The one essential in the transportation of concrete from the place of mixing to the forms is that no opportunity be afforded for a segregation to take place between the mortar and the coarse aggregate. Chutes down which the concrete flows are often considered objectionable, if of any considerable length, for just this reason. Chutes may be so constructed, however, by making the slope conform to the degree of wetness of the mix, that little difficulty is encountered by reason of segregation.

On small jobs concrete is usually transported in wheel-barrows. On larger work large dump-buckets, or cars carrying dump-buckets, are commonly used. With modern fairly slow-setting cement there is little danger of the concrete setting before reaching the place of deposition except in case of interruption of the work, in which event especial care must be exercised to see that no concrete be left in wheel-barrows or other conveyances. Regauging of concrete which has set or partially set, by stirring up the mass with or without additional water, is never permissible.

Concrete should be deposited in nearly horizontal layers only a few inches thick and should never be allowed to flow down a slope, since in that event segregation of the fine and coarse material will invariably take place. On work where absolute continuity of the concrete is required the deposition must be carried on continuously until the work is completed. There will invariably be a joint or plane of weakness where one day's work is stopped and deposition of new concrete resumed after twelve to fifteen hours. It is therefore important that the work be so planned and prosecuted that the planes of weakness lie in the direction of least stress in the finished structure.

113. Consistency, Ramming or Puddling. The materials should be mixed wet enough to produce a concrete of such a consistency as will flow into the forms and about the reinforcement if such be present. At the same time it must not be so wet as to cause difficulty through segregation of the coarse aggregate and the mortar before final deposition.

Formerly, it was the practice to mix concrete so dry that an excessive amount of tamping was necessary to compact the mass and prevent bridging of the fragments of the larger aggregate, causing voids.

Specifications now usually require a mix so wet that ramming or tamping is unnecessary, a dense concrete and smooth surfaces being obtained by simply puddling the mass until the ingredients have settled into their proper place by gravity and any surplus water has been forced to the surface. In order to have a good finish it is well to make use of a straight shovel along each side of the forms, forcing all the larger fragments of the aggregate a short distance back from the face.

114. Bonding to Old Work. Since joints cannot be avoided in work not carried on continuously to completion, every reasonable precaution should be taken to make the bond of new to old work as strong as possible.

In massive work with horizontal joints the question is one of less importance than in thin walls or situations requiring water-tightness. In the former case it will probably suffice to simply clean and wet the old work before laying new concrete. Where walls are thin, or waterproofness is required, the concrete previously placed should be roughened, thoroughly cleaned of foreign material and "laitance," and slushed with a thin grout of either neat cement or rich mortar, the proportion of sand to cement in the latter case not exceeding two to one.

Laitance is a whitish scum which is washed out of concrete when there is excess of water, as when concrete is deposited in water or when water collects in pools on the surface of freshly laid concrete. The laitance consists of the finest flocculent matter in the cement together with dirt from the aggregates. The composition of laitance is practically identical with the composition of the cement itself. This flocculent material remains suspended in the water for a long time, giving it a milky appearance, and settles slowly on the surface of the concrete. The laitance hardens only very slowly and never acquires much strength, so that, if not removed, it seriously interferes with the bonding of successive layers of concrete.

115. Facing of Walls. The cheapest and most satisfactory method of obtaining a smooth face on concrete walls is by the use of a straight shovel or slice bar along the forms, forcing the coarser aggregate back from the surface.

Plastering with mortar after removal of forms is useless, because it will almost invariably scale off, owing to poor bond and unequal expansion. Imperfections in the face must, of course, be patched up, but this should be done with a mortar of the same mix as that used in the concrete to prevent different-colored patches showing.

Washing with a thin grout immediately after removal of forms is beneficial to some extent, and if the layer is not of appreciable thickness so as to form a continuous film it will not scale off.

A layer of special mortar is sometimes placed next the forms by means of a movable sheet-steel diaphragm which is inserted in the form and kept the required distance from the face by suitable spacing blocks. The concrete and mortar are now filled in simultaneously, and the diaphragm is raised as the work proceeds, so that it is always only a few inches below the surface. In this manner the two mixes come into contact with each other before setting begins and the bond will not be imperfect.

A "rubbed finish" is sometimes obtained by removal of the forms while the concrete is still green and rubbing with a wooden float. A "tooled finish" is sometimes produced after the concrete has partially hardened, by use of the tools which are used in finishing stone. A "brushed finish" is produced by brushing the green concrete with a stiff wire brush, after which a dilute solution of hydrochloric or muriatic acid is applied with a brush. The acid thoroughly cleans the stone and brings out the natural colors, but must be immediately removed by slushing with water. Otherwise acid discoloration will occur.

116. Depositing under Water. In many classes of subaqueous concrete construction it is possible to use cofferdams or caissons from which the water may be excluded. The placing of the concrete will then not differ materially from methods commonly used on land. When such methods are not feasible, the problem becomes one of considerable difficulty.

Cement, sand, and stone are heavy enough to sink in water, but the laitance and some cement which is not immediately hydrated will be floated away. This therefore represents a considerable loss of cement. The problem is entirely one of placing the concrete in its final position under water without allowing the excessive formation of laitance or washing out of cement.

Many methods have been used with a greater or lesser degree of success, among which the following may be mentioned:

The "tremie," a device often used, consists of a large tube of wood or sheet metal, so constructed as to make its length adjustable, and provided with a hopper at the top. In use the tremie is supported vertically in the water by barges or derricks, provision being made for horizontal movement of the tube over the area occupied by the work. The lower end is allowed to rest on the bottom or is closed by a valve arrangement, and the tube is filled with concrete. The tremie is now lifted a short distance and the concrete allowed to escape as the device is moved over the required area. A layer of concrete of any desired thickness is thus deposited, the tube being kept continuously filled to a point above the water line. This method does not entirely prevent the formation of laitance and loss of cement, but it has been found satisfactory on many large works.

Buckets, so constructed as to allow the material to flow out from the bottom, the top being closed, are used in a manner similar to the use of the tremie. A derrick lowers the closed bucket into place, the bottom doors are opened, and the material escapes as the bucket is hoisted. Buckets so used are usually of large capacity, since if several yards of concrete escape at once the material compacts better with less loss of cement.

Bags of all kinds, from paper to burlap and heavy jute, have been employed in depositing subaqueous concrete. Paper bags are usually of a brown paper which is destroyed shortly after immersion. Cloth bags are not removed or destroyed but, the cloth being very porous, enough cement escapes to bind the bags quite firmly together. Bags are never filled completely, as it is desirable to have them pack together closely.

Concrete is sometimes mixed and deposited in water altogether dry, sacks or buckets being used. This method is entirely unsatisfactory, as the escape of cement is very great and it is impossible to obtain as uniform and dense a concrete as is obtained by any of the above methods, using concrete mixed with water in the usual manner.

THE MAKING OF CONCRETE UNDER SPECIAL CONDITIONS

LAYING CONCRETE IN FREEZING WEATHER

117. Effect of Low Temperatures. Low temperatures have a marked effect in increasing the setting time of cement. If water in concrete or mortar freezes before the cement has set, it is not available for the chemical action of setting and hardening and hence the concrete or mortar will not set at all until the ice melts. The above facts must be borne in mind when removing forms from concrete placed during cold weather.

If the temperature hovers above the freezing-point for some time after concrete is deposited, there is a possibility of the water drying out before the greatly delayed setting has taken place. If, however, the concrete has begun to set before the temperature drops considerably below the freezing-point, the expansion of the water in solidifying produces an expansive force in excess of the cohesive strength of the green concrete. This action results in destruction of the bond and crumbling of the concrete when the ice melts.

If the temperature does not fall more than a degree or two below freezing, the result may simply be the further delaying of the set without appreciable injury. This is possible because the water may not have frozen, owing to the chemical heat of combination afforded by the slowly setting cement.

118. Methods of Concreting in Freezing Weather. "Concrete should not be mixed or deposited at a freezing temperature, unless special precautions are taken to avoid the use of materials containing frost or covered with ice crystals, and to provide means to prevent the concrete from freezing after being placed in position and until it has thoroughly hardened."

Work may be carried on during freezing weather by either of two methods — keeping the materials and the work at a temperature above the freezing-point until the concrete has had time to set, or, for temperatures only a few degrees below freezing, by the addition to the water used in mixing of a substance which lowers the freezing-point of water.

The first method is more generally recommended and used. The sand and stone are heated by piling them over heated iron conduits or steam pipes, and the water is heated in a large supply tank fitted with steam coils. Care should be taken not to have the materials too hot.

The work may be protected from frost by covering with earth, canvas, hay, boards, etc., if the temperature falls but very little below freezing, but in case of heavy frost heat must be artificially supplied. A common but rather unsatisfactory method consists in covering the top of the work to a depth of several inches or a foot with manure, which is in turn covered with boards or canvas. The chemical action of decomposition of the manure is a source of sufficient heat to prevent frost reaching the work.

When the work is in the nature of a building or structure of limited extent it is practicable to house it in with sheathing or canvas. Fires are then kept going continuously in salamanders within the enclosure, thus keeping the temperature above freezing.

The second method, by reducing the freezing-point of water, is not generally considered as favorably as the above-described methods, but is cheaper and hence often used. Common salt or calcium chloride is most commonly used. Approximately 1 per cent of salt in the mixing water lowers the freezing-point 1° F. (0.55° C.). Beyond 10 per cent salt becomes ineffective and injurious. Alcohol, glycerine, and other chemicals have an effect similar to that of salt in reducing the freezing-point of a water solution. All are, however, less effective than salt, and the latter being cheaper is commonly preferred.

CONCRETE IN SEA WATER. EFFECT OF ALKALI ON CONCRETE

119. Action of Sea Water on Concrete. The behavior of concrete in sea water is a problem which has occupied much of the attention of engineers for many years. The question has often been discussed, and many attempts have been made to determine experimentally the exact action of sea water upon concrete, and the causes of that action.

Many concrete structures in sea water have remained intact and uninjured for many years; a few, constituting a small minority of all marine structures built, have been injured or destroyed under the same conditions. In view of the conflicting results obtained experimentally it is difficult to explain why certain marine structures remain sound indefinitely, while others disintegrate more or less rapidly.

It is known that the salts in the sea water (magnesium sulphate, magnesium chloride, sodium chloride, and calcium sulphate) react in some way with the constituents of cement. It appears further that cements high in free lime or especially high in alumina are especially subject to the destructive attack of the salts in the sea water.

The chemical action is accompanied by various physical phenomena: sometimes the mass swells, cracks, and gradually falls apart, sometimes the mortar softens and gradually disintegrates, and occasionally a crust forms on the surface which later cracks off. Often the disintegration is facilitated by freezing or by imperfect construction, especially when proper means have not been taken to prevent the inclusion of the laitance, which forms to a much greater extent in salt water than in fresh water.

120. Expedients Adopted to Prevent Injury by Sea Water. Foremost among the precautionary measures to be taken in the construction of marine structures of concrete is the securing of as dense and impermeable a concrete as possible.

An outer shell of especially dense materials is sometimes used with good results on marine structures. In this case a few inches of rich mortar (1 : 2 or 1 : 2½) is made to enclose and protect the inner portion of the concrete. It is necessary that this outer layer be cast at the same time as the inner portion in order that there may be a perfect bond between the two mixes.

Sometimes certain substances, such as barium chloride, are dissolved in the mixing water for the mortar used on the outer shell. These, upon contact with the salts of the sea water, form insoluble sulphates which tend to close the pores in the mortar.

Sesquicarbonate of ammonia or magnesium fluosilicate is sometimes used as a coating applied to the face of the finished work by brush or spray. These tend to form an impervious film of carbonate of lime in the one case, and insoluble calcium fluoride and lime silicate in the second case, thus stopping the pores. These methods remain effective only so long as the impervious coating remains intact.

121. Effect of Alkali on Concrete. The effect of alkali on concrete is a problem resembling in many respects that of the action of sea water on concrete. The problem is of especial interest in connection with concrete construction in the arid regions of the West, where soluble salts are present on the soil to an extent not usually found elsewhere.

The principal salts encountered in alkali waters usually include: magnesium sulphate, calcium sulphate and sodium sulphate, magnesium chloride, sodium chloride, and potassium chloride, together with carbonates of magnesium, sodium, and potassium. Of these the sulphates appear to be most active in causing disintegration of concrete; the chlorides also are active, while the carbonates appear to be without effect.

From the physical point of view the action resembles the action of frost, except that it is more rapid. There exists, apparently, a disruptive force which destroys the bond and causes disintegration. This action appears to proceed most rapidly in the parts of a structure subjected to alternate wetting with alkali water and drying in the air. In porous concrete the action proceeds much more rapidly than in dense concrete.

The remedy is, as in the case of marine structures, the securing of the densest possible concrete, thus preventing injury by the exclusion of the salt-bearing waters.

CONCRETE WHERE WATER-TIGHTNESS IS REQUIRED

122. Proportioning the Mixture. The permeability of concrete is closely related to the porosity or void content, but the relationship is not always direct and by no means constant, since the continuity and size of the pores determines permeability more than does the actual percentage of voids.

Dense concrete may be most readily obtained by a careful proportioning of the mixture based on careful selection and mechanical analysis of the aggregates. Usually only the outer layer having a thickness of a few inches need be thus carefully proportioned. It may even be advisable, for this outer shell, to use a mortar of 1 : 2 mix, in which case, with careful deposition, practical imperviousness against small heads may be secured.

123. Use of Waterproofing Compounds. Waterproofing compounds may be classed in two general divisions: Inert fillers — that is, those materials, such as clay, finely ground sand, hydrated lime, etc., which serve simply as void fillers and do not have any action upon the cement nor change in themselves — and active fillers, which react with certain of the constituents of the cement to form inert insoluble compounds, or in the presence of the cement react with water and precipitate insoluble compounds. In this latter class are included many patented compounds all consisting essentially of stearic acid combined with soda and potash or lime.

Inert fillers are added to the dry cement before mixing the mortar or concrete in percentages usually amounting to from 10 to 20 per cent of the weight of the cement. Active fillers are also mixed with the dry cement before mixing, but the percentage used is not often more than 2 per cent by weight of the cement. Upon the addition of water to a stearate of lime, a lime-soap is formed which is insoluble in water. In case the stearic acid is combined with soda or potash, instead of lime, the soda-soap or potash-soap is readily soluble, and these must combine with the lime in the compound to form the insoluble lime-soap. This is readily accomplished, since the stearates in the compounds never amount to more than a very small percentage, the greater part of the material being hydrated lime and magnesia.

All of the inert fillers are fairly effective in reducing permeability, clays being slightly more effective than ground sand or feldspar. The active fillers are also usually more or less effective in reducing permeability, though often to a lesser degree than some of the inert materials. The inert fillers have little effect upon either tensile or compressive strength of mortars and concretes. The active fillers, on the other hand, usually reduce both the tensile and the compressive strength of rich mortars and only in very lean mixtures is their injurious effect upon strength no longer noted.

Hydrated lime used in amounts not exceeding 10 to 15 per cent of the cement is one of the best materials for waterproofing concrete available. Its action appears to be chiefly mechanical, in that it produces a fat, viscous mortar in which separation of sand and cement is reduced to a minimum and a uniform dense concrete secured.

124. Layers of Waterproof Material. Layers of waterproof paper or felt applied with a coating of coal tar or asphalt are sometimes used as an impervious course in underground concrete walls, floors, etc. Asphalt is much superior to coal tar, since the latter deteriorates when long exposed to moisture. The asphalt is spread hot on the concrete already placed, followed by alternate layers of paper or felt and hot asphalt. Usually the waterproof course is laid 3-ply, 4-ply, or even 5- or 6-ply.

Such a course is finally coated with asphalt again, and the remainder of the concrete deposited in place at once. A distinct joint in the masonry is necessarily formed in the plane of the impervious course, and this fact must not be overlooked in designing walls and floors in which a waterproof layer is incorporated.

125. Surface Treatments for Waterproofing. The principal classes of coating compounds are the following:

Oil Paints and Varnishes. These are usually not specially made for use as cement paints, but are ordinary paints consisting of resins, pigments, driers, etc., mixed with linseed oil. They are superficial, inelastic, short lived, and of little value.

Bitumens. These include asphalt, petroleum residuum, and coal-tar pitches. All are applied as a hot liquid, with or without waterproof paper or felt, and become solid at ordinary temperatures. Bitumens give fairly satisfactory results owing to their great elasticity and durability except when exposed to the weather.

Liquid Hydrocarbons. These include solutions of paraffin in benzine or benzol, and emulsions of petroleum oil or fat in water secured by the use of ammonia. They are superficial, but may prove effectual until their efficiency is destroyed by the opening up of small surface cracks. on the face of the masonry.

Soaps. Soaps are used either solid or in solution, and also in connection with alum. They are soluble in water, so their efficiency is limited to the possibility of chemical action resulting in the formation of insoluble lime-soap.

Cements in which Water-repellent Material has been Incorporated during Manufacture. These may be used as an exterior coating, or they may be incorporated in the entire concrete. They differ in no respect from ordinary cement with which one of this class of waterproofing compounds has been mixed just prior to concrete or mortar mixing, and hence need not be separately discussed here.

The physical properties of concrete are discussed in Chapter I of this section.

SECTION 3

CHAPTER I

BUILDING STONES, STONE MASONRY AND ROAD METAL

BUILDING STONES

1. Stone as a Structural Material. The term "building stone" is applied to all those classes of natural rock which are employed in masonry construction. Stones form, with the exception of timber, the only important class of materials which may without alteration of their natural state be used directly in the construction of engineering works.

Aside from purely structural uses, great quantities of stone are utilized on other kinds of engineering construction such as for flagging and curbing, for paving blocks and as crushed stone for road building, railroad ballast and concrete aggregate.

2. Classification of Rocks. *Geological Classification.* In the usual geological classification rocks are divided into *Igneous Rocks* formed by consolidation from a fused or semi-fused condition; *Sedimentary Rocks*, formed by the solidification of material transported and deposited by water; and *Metamorphic Rocks*, which are formed by the gradual change of the structure and character of igneous or sedimentary rocks through the agency of heat, water, pressure, etc. Granite, greenstone, basalt, and lava are common examples of igneous rocks; sandstone, limestone, and shale, of sedimentary rocks; and gneiss, marble and slate, of metamorphic rocks.

The geological classification has only a limited bearing upon the consideration of rocks as building stones. Igneous rocks are usually non-laminated and more or less crystalline in structure; sedimentary rocks are distinctly stratified, having, therefore, original cleavage planes; metamorphic rocks may or may not be laminated, depending upon the pressure encountered during metamorphism. Most of the metamorphic rocks which have been changed largely through the agency of pressure, water, and heat are crystalline in structure.

*Physical Classification.** With respect to the structural character of

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* I. O. Baker, "Masonry Construction." Baker uses the term "stratified" in a broad sense to include both bedded sedimentary and banded metamorphic rocks.

large masses, rocks are divided into *stratified* and *unstratified.* The structure of unstratified rocks is, for the most part, an aggregate of crystalline grains firmly adhering together. Granite, trap, basalt, and lava are examples of this class.

Stratified rocks may be divided into the following classes according to physical structure:

Compact crystalline structure (marble).
Slaty structure (clay and hornblende slate).
Granular crystalline structure (gneiss, sandstone)
Compact granular structure (blue limestone).
Porous granular structure (minute shells cemented together).
Conglomerate (fragments of one stone embedded in mass of another).

Chemical Classification. Stones are divided according to the chemical nature of their predominating constituents into the following three classes:

Siliceous stones, in which silica is the predominating chemical constituent. (Granite, syenite, gneiss, mica-slate, greenstone, basalt, porphyry, quartz-rock, hornblende-slate, and sandstone.)

Argillaceous stones, in which alumina is the important constituent. (Slate, and graywacke-slate.)

Calcareous stones, in which carbonate of lime is the predominating constituent. (Marble and limestone.)

STONE QUARRYING AND CUTTING

3. Methods of Quarrying.* After the exposure of rock by the stripping of the surface soil the quarrying is done by hand tools, by machine tools, by the use of explosives, or by a combination of two or more of these methods.

Hand Methods. Hand methods may be employed when the stone occurs in thin beds. Such stone, which is usually inferior in quality, may be taken out by use of the drill and hammer, wedges, plug and feathers, pick, crowbar, etc. Holes $\frac{3}{8}$ to $\frac{3}{4}$ inch in diameter are drilled a few inches apart in rows. The rock is thereupon split in the plane of the holes by the driving in of wedges or by use of plug and feathers. The plug is a short steel wedge with plane faces, and the feathers are wedges having one cylindrical and one plane side. When a plug is inserted between two feathers the three will slip into a cylindrical hole, and a great splitting force in one direction only may be exerted by driving the plug.

Machine Methods. The use of machinery driven by steam, compressed air, or electric motors, is usually combined with hand methods

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* See also Bull. 106, Dept. Int. Bureau of Mines. "The Technology of Marble Quarrying."

whenever quarrying operations are conducted on any but a very small scale. The commonest application of power-driven machines in the quarry lies in the use of machine drills which cut much more rapidly than hand drills and are usually arranged to work at any angle.

When it is desirable that the stone be removed in rectangular blocks advantage is always taken of the natural cleavage planes of the rock. The quarry is worked in benches, the width of which correspond to the dimensions of stones that can be handled, and the height of which corresponds to the thickness of the rock strata. Rows of holes are drilled parallel and perpendicular to the edge of the bench, wedges or plug and feathers are then inserted in the holes, and the blocks of rock thus split along the planes of the holes. "Under-cutting," the drilling of a series of horizontal holes, is resorted to when not rendered needless by the stratification of the rock.

When the rock need not be removed in large or rectangular blocks, particularly when the rock is to be subsequently crushed for road stone, ballast, or concrete aggregate, explosives may be used in the drilled holes.

When stone is quarried for building and monumental purposes on a scale sufficient to justify the use of more elaborate mechanical equipment than the ordinary machine drills, or when very large rectangular blocks of stone are desired, it is the practice to use a special machine called a "channeler." The channeler is a machine operating on rails or guide bars, which operates a gang of cutters with which long and deep, but narrow, channels are cut as the machine slowly moves along. The sides of large blocks are thus freed, and the blocks are subsequently freed from their beds by wedging, or undercutting and wedging, as may be necessary.

4. Stone Cutting.* *Surface Dressing.* All stones used in building come under one of three classes:

I. Rough stones.
II. Stones roughly squared and dressed.
III. Stones accurately squared and finely dressed.

The first class includes all stones used as they come from the quarry without any special preparation.

The second class includes stones roughly dressed on beds and joints with the face hammer or axe. The distinction between this class and the third class lies in the closeness of the joints. When the dressing on the joints is such that the general thickness of mortar required is ½ inch or more the stones properly belong to this class.

Three subdivisions of this class may be made, depending on the character of the face of the stone:

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* A description of stone cutting tools and their use in dressing stone may be found in Vol. 6, Trans. Am. Soc. C. E., also in Baker's "Masonry Construction."

Quarry-faced stones are stones whose faces are left untouched as they come from the quarry.

Pitch-faced stones are those the edges of whose face are made approximately true by use of the pitching chisel.

Drafted stones are those whose faces are surrounded by a chisel draft, the space inside being left rough. This method is not ordinarily used on this class of stones.

The third class includes all stone dressed to smooth beds and joints so that the thickness of mortar joints is less than $\frac{1}{2}$ inch.

As a rule all of the edges of cut stone are drafted. Inside the draft any of the following methods of dressing the face may be used.

Rough pointed; projections $\frac{1}{2}$ or 1 inch. (Used on limestone and granite.)

Fine pointed; projections less than $\frac{1}{2}$ inch.

Crandalled; effect same as fine pointed except that the tool marks are more regular, $\frac{1}{8}$-inch projections.

Axed; or pean-hammered; face covered with parallel chisel marks.

Tooth-axed; same finish as fine pointed.

Bush-hammered; (usually used only on limestone), follows rough pointing and tooth-axing.

Rubbed; sawn surfaces smoothed by grit or sandstone (used on sandstones and marble).

Diamond panels; face inside of draft cut to flat pyramidal form.

PROPERTIES OF BUILDING STONES *

GENERAL DESCRIPTION OF STONES

5. Granite. Granite is the term applied to a plutonic,† igneous rock, whose structure varies from finely granular to coarsely crystalline. Its principal mineral constituents are quartz and feldspar, with varying amounts of mica, hornblende, etc. Its prevailing color is gray, though greenish, yellowish pink, and red shades are found more or less frequently.

Granite is more extensively used as a building stone than any other class of igneous rock. It works with difficulty, due to its hardness and toughness, but its quarrying is usually facilitated by the existence of planes of weakness, the "rift" extending either in vertical or horizontal

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* For detailed information concerning building stones consult "Stone for Building and Decoration" by G. P. Merrill. Also see "Building Stones and Clay Products" by Dr. Heinrich Ries, and "Engineering Geology" by Dr. Ries and Dr. T. L. Watson.

† Plutonic rocks are igneous rocks formed by the solidification of molten material prior to its emergence on the earth's surface; volcanic rocks have cooled on the earth's surface.

planes, and secondary planes, "the grain" along which the rock may be less readily split at right angles to the rift. As a rule the quarry rock shows "joints" or fissures in the direction of the rift, and often a secondary series of joints exists in the direction of the grain. The removal of rectangular blocks of large or small dimensions is thus facilitated.

Granite is used for foundations, base courses, columns, and steps in building construction, and is suitable for any situation where strength or hardness is required. To a limited extent it is used as an ornamental stone, its suitability being dependent upon color and texture. Granite of excellent quality may be obtained in any of the New England States, in most of the Southern States, in the Rocky Mountain Region, and in California and Minnesota.

6. Gneiss. Gneiss has the same composition as granite and resembles granite in appearance but differs in physical structure, the various constituents being arranged in more or less parallel bands. The rock therefore splits readily into flat slabs, which renders quarrying less expensive than in the case of granite and makes the stone valuable for foundation walls, street paving, curbing, and flagging. It is found in the same general localities as granite.

7. Limestones. The term limestone is commonly applied to all stones which, though differing from one another in color, texture, structure, and origin, possess in common the property of containing carbonate of lime (calcite) or calcite and the double carbonate of lime and magnesia (dolomite) as the essential constituent. In addition they contain as impurities oxides of iron, silica, clay, bituminous matter, talc, etc. Different limestones may be listed according to structure and composition and mode of origin under the following heads:

8. Crystalline Limestone or Marble. The term "marble" is commonly applied to any limestone which will take a good polish. It is properly applied only to those limestones which have been exposed to metamorphic action and rendered more crystalline in structure.

The structure of marbles varies from finely crystalline to coarsely crystalline. Marbles are found in almost every conceivable color, and are often richly streaked with several colors. All varieties of marble work well, the finer grained white marble being especially adapted to carving. Marble has been used in this country principally for interior decoration, but many varieties are entirely suitable for exterior construction. Most of the colored and mottled and veined marbles are imported into this country. Quantities of white and black marbles are quarried, however, in Vermont, Georgia, New York, Pennsylvania, Maryland, and California, and some beautiful colored and mottled marbles are obtained from Tennessee and Vermont.

9. Compact Common Limestones. These are usually quite fine-grained limestones of varying textures and colors, giving rise to many varieties. The best known and most widely used American limestone is the *Bedford limestone.* This is a light-colored, fine-grained, oölitic limestone (made up of small rounded concretionary grains cemented together by carbonate of lime). It is a light gray in color, works with remarkable ease, and hardens on exposure. It has been extensively used for exterior construction of buildings, for bridge piers, and for heavy cut-stone masonry in general. It is quarried at Bedford, Indiana, and Bowling Green, Kentucky. *Travertine* is a compact fine-grained limestone deposited on the surface by running streams and springs. The term *onyx* or *onyx marble* is often though incorrectly applied both to *travertine* and to *stalactite* and *stalagmite,* which are deposits of limestone, often beautifully banded and streaked with colors, formed on the roofs, walls, and floors of caves.

Onyx marbles (using the term in the sense above mentioned) differ from marbles of the common type only in that they are purely chemical deposits rather than products of metamorphism from pre-existing calcareous sediments. The travertine varieties are products of deposition from hot springs carrying lime carbonate in solution, together with small quantities of iron and manganese carbonates and other more rarely encountered constituents. The stalactite and stalagmite varieties differ only in manner of formation, being cold-water depositions made on the roofs, walls, and floors of limestone caves. Both varieties owe their banded structure and variegated colors to the intermittent character of the deposition and the varying content of impurities like the metallic oxides.

The onyx marbles are considered the most beautiful of decorative stones, they cut readily and take a high finish, and are largely used for interior decorations.

A large part of the onyx marble used in the United States is imported from Mexico. There are, however, important quarries in Arizona and California. The foreign onyx comes largely from Algeria and Italy.

10. Sandstones. "Sandstones are composed of rounded and angular grains of sand so cemented and compacted as to form a solid rock. The cementing material may be either silica, carbonate of lime, an iron oxide, or clayey matter." *

Sandstones vary greatly in color, hardness, and durability, but include many of the most valuable varieties of building stone for exterior construction. The qualities of sandstones as a structural material depend

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* Merrill, "Stones for Building and Decoration," p. 299.

largely upon the character of the cementing material, the character of the sand grains being very nearly the same for all, i.e., a pure quartz. If the cement is siliceous the stone is light colored, hard, and sometimes difficult to work, but very durable. If iron oxides comprise the greater part of the cementing material, the color is a red or brownish tone and the stone usually is not too hard to work well, though it does not always prove very durable. If the cementing material is lime carbonate the stone is light colored, soft, and easy to work, but less durable than either of the above varieties. Clayey sandstones are the poorest class. They are soft and easily cut, but are particularly subject to the disintegration caused by weathering because of their high absorption. Some sandstones contain very little cementing material, but owe their strength largely to the pressure under which they have been solidified. Such stones are a light gray color, work easily, and if they possess sufficient cohesive strength, are very durable. A few sandstones contain varying amounts of grains of feldspar or mica, in which case they are inferior to ones the grains of which are entirely quartz. The following are the principal well-known sandstones in this country:

The brownstones of Connecticut, Massachusetts, Pennsylvania, New Jersey, North Carolina, and a few other localities, are handsome dark reddish-brown stones, fine grained, easy to work, and capable of taking a good "rubbed" finish. With the exception of the Massachusetts stone, they occur in distinctly laminated beds and must be used on their natural beds. These stones, having iron oxides for a great part of their cementing material, are usually subject to the disintegrating effect of atmospheric agencies and therefore do not usually rank especially high in durability.

The *Ohio stone, Berea sandstone,* or *Amherst stone* is a fine-grained light buff, gray, or blue-gray stone having silica for the most part as its cementing material, the amount of cement being low. These stones cut and work readily, are well adapted to carving, and, when those portions containing iron pyrites are excluded, are very durable. The principal quarries are located at Amherst, and at Berea, Ohio, and the stone has been largely used in the cities of the Middle West.

The *Waverly stone* is a fine-grained homogeneous stone of a light drab or dove color, quarried only in the vicinity of Cincinnati, Ohio. It is sometimes called the *Euclid bluestone.* It resembles the Ohio stone except that it has a finer and more compact texture. It works easily and, except for portions containing iron sulphides, is a handsome and durable stone.

The *Potsdam red sandstone* from Potsdam, New York, is composed wholly of quartz grains cemented by a small amount of silica with just enough iron oxide to give it a reddish or brownish-red color. It is fine-grained, handsome in appearance, works well though rather hard, and is the strongest and most durable of sandstones after becoming hardened by seasoning. Its composition being practically quartzite, it is as strong as granite, and particularly non-absorptive, making it practically proof against all disintegrating influences.

The *Lake Superior stone* is a Potsdam stone of medium fineness. It has a light red-brown color and is often spotted gray. It is quarried largely at Marquette, Michigan. This stone resembles the Potsdam stone of New York, except that it has rather more cementing material and therefore is not quite as hard and strong. It works well and is very durable.

The *Medina sandstone* of Western New York is a hard moderately fine-grained stone, either red or gray in color. The red variety resembles the Potsdam stone, except that it is not so fine in texture, and is similarly used. The gray variety is rather too hard to work for general building purposes, but is largely used for street paving and curbing, where it has the advantage of some other hard stones, like granite or trap, in that it does not wear smooth.

The *Rocky Mountain sandstones* include many varieties of excellent building stone. The best-known ones are very fine-grained, soft-textured stones of a dark-brown color. They work well, take a good "rubbed" finish, and are fairly durable.

11. Slates. Ordinary slate is a siliceous clay, compacted and more or less metamorphosed after deposition as fine silt on ancient sea bottoms. The pressure due to thousands of feet of overlying material is largely responsible for the solidification of the clay into rock having very marked cleavage planes. The most valuable characteristic of slate is its pronounced tendency to split into thin sheets having smooth regular surfaces. The non-absorptiveness of slate, its great toughness and mechanical strength and its non-conductiveness for electric currents, are other valuable attributes. Slate must be split while fresh from the quarry, and the quarry loss amounts to more than 60 per cent of the rock.

PHYSICAL AND MECHANICAL PROPERTIES OF BUILDING STONES

12. Selection of Building Stone. The selection of a proper stone for construction purposes is dependent to a great extent upon the climate where the stone is to be used. The range of changes of temperature, the average humidity of the atmosphere, the possibility of acid fumes in the atmosphere of many cities, and the possibility of the stone being subjected to high temperatures by fire are among the considerations which must be carefully taken into account. Very often the only considerations given weight by an architect are the cost and the appearance. He is very likely to take great care in securing a color which harmonizes with the general scheme of the structure on which it is used, while wholly overlooking the question of satisfactory weathering qualities.

The actual mechanical strength of stone is seldom of great importance because of the fact that stones in masonry structures can never be loaded to their full capacity because of the comparative weakness of the mortar joints.

13. Properties of Various Stones. *Durability.* The durability of stones depends upon ability to withstand weathering agencies, and the structure, texture, and mineral composition are the real determining factors. Joint planes, cracks, or other structural imperfections afford an opportunity for water to enter and for disintegration to begin through frost action. Stones of coarse-grained texture are more subject to the disintegrating influence of temperature changes than fine-grained ones, and dense stones, owing to their practical imperviousness, are less likely to be injured through frost action than are porous ones. Of the mineral compounds which make up our common rocks, sulphides are among the least resistant to weathering agencies; iron compounds in general are undesirable in large quantities; calcium and magnesium carbonates weather rather rapidly; aluminates weather less rapidly; silicates or silica are most resistant to decay. The fact must not be overlooked in this connection that the three factors, structure, texture and mineral composition, are simultaneously operative so that a very dense fine-grained stone made up principally of carbonate may weather well, while a porous or structurally imperfect stone made up principally of silica may weather poorly.

The estimated life of various building stones is indicated by the following table quoted by Ries and Watson * from the observations made by A. A. Julian in New York City.

Kind of stone.	Life in years.
Coarse brownstone	5 to 15
Fine laminated brownstone	20 to 50
Compact brownstone	100 to 200
Bluestone (sandstone) untried	Perhaps centuries
Coarse fossiliferous limestone	20 to 40
Fine oölitic (French) limestone	30 to 40
Marble, coarse, dolomitic	40
Marble, fine, dolomitic	60 to 80
Marble, fine	50 to 100
Granite	75 to 200
Gneiss	50 years to many centuries

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* "Engineering Geology," p. 432.

Absorption. The absorption or absorptive power of stones is represented by the weight of water that can be absorbed expressed as a percentage of the dry weight of the stone. Absorption is directly dependent upon the porosity of stones, though this relation is not necessarily any fixed ratio. The gain and loss of moisture when a stone is first exposed in a damp or wet situation, and then dried, will be most rapid if the pores are large or straight, and least rapid if they be small or tortuous.

It appears from tests * that the absorption of igneous and metamorphic rocks rarely exceeds ½ of 1 per cent. The sandstones absorb at least ten times as much as granites, marble and slate and the limestones absorb even more moisture than the sandstones.

Expansion and Contraction. Stones, like most other materials, expand upon being heated and contract when cooled. Unlike most other materials, however, they do not quite return to their original volume when cooled after heating, but show a swelling which is permanent. Experiments made at the Watertown Arsenal by heating from 0° to 100° C. (32° to 212° F.) and cooling through the same range, showed the permanent increase in length for the various stones tested to be from 0.02 per cent to 0.045 per cent.

The coëfficient of temperature expansion per degree Fahrenheit for various building stones was found in a series of tests at the Watertown Arsenal to be very variable, the range of values found being as follows: Granites, 0.00000311 to 0.00000408; limestones 0.00000375 to 0.00000376; marbles 0.00000361 to 0.00000562; sandstones 0.00000501 to 0.00000622.

Frost Resistance. Stones can be disintegrated by frost action only when the pores are practically filled with water before exposure to freezing temperatures. As stones seldom are used under such conditions that the maximum amount of water is absorbed, instances of injury to good building stones by frost action are very rare. Experimental work on the resistance of stones to disintegration by frost indicates that the pores can be filled with water, so that the subsequent expansion upon freezing will cause rupture, only by the use of high pressure or by first exhausting the air by a vacuum. It will be apparent therefore that only stone of the greatest absorptive power combined with low structural strength can ever be injured by frost action under the conditions encountered in practice.

Fire Resistance.† Practically all building stones are seriously injured if exposed to such high temperatures as may be encountered in case of fires, and particularly so if exposed to the combined action of fire and water. The cause of disintegration is usually explained to be the internal

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* "Engineering Geology," p. 437.

† "Engineering Geology," p. 446.

stresses caused by unequal expansion of unequally heated portions of the material. This explanation is rendered more forcible by the observed fact that if highly heated stones be suddenly cooled on the exterior by application of water, the resultant disintegrating action is much more pronounced than when the cooling is slow. The texture of the stone and the relative coefficients of expansion of its individual mineral constituents probably are also factors of importance.

Experience has shown that granites are particularly poor fire resistants. Probably on account of the irregularity of the structure and the complexity of the mineral composition, granites crack irregularly and spall badly. The coarse-grained granites are most susceptible to the action of fire and water, and the gneisses often suffer even more severely because of their banded structure.

Limestones suffer little from heat until a temperature something over 600° C. (1112° F.) is reached, at which point the decomposition of the stone begins, owing to the driving off of carbon dioxide. The stone then has a tendency to crumble, due to the flaking of the quicklime formed. Curiously enough the limestones do not suffer so much by sudden cooling as by slow cooling.

Marbles, owing to the coarseness of the texture and the purity of the material, suffer more than limestones at temperatures below the point where calcination begins. The cracking is irregular and the surface spalls off as in the case of granites.

Sandstones, especially if of a dense, non-porous structure, suffer from high temperatures and sudden cooling less than most other building stones. The cracking of sandstones which does occur, appears mostly in the planes of the laminations, which should be horizontal planes as the stone is set. These cracks are therefore not as serious as irregular cracks. Sandstones whose cementing ingredient is silica or lime carbonate are better fire resistants than ones whose grains are bound by iron oxide or clay.

Mechanical Properties of Stones. The following tabulation of mechanical properties of the principal classes of building stone has been compiled from the Watertown Arsenal Tests of 1894 and 1895 to serve as an approximate guide in the selection of a building stone.

It will be noted by reference to the table that the properties of the different varieties of building stones of the same general class vary greatly. It is, therefore, not advisable to use the average strength indicated, except in a very general way, the safe working stress being determined by the use of a large factor of safety. (Taken at from 15 to 35, depending upon the structural use made of the stone, and the amount of variation shown in tests of the particular variety of stone used.) For

MECHANICAL PROPERTIES OF BUILDING STONES

Name. Locality.	Comp. strength. Lbs. per sq. in.	Mod. of rupture. Lbs. per sq. in.	Shearing strength. Lbs. per sq. in.	Weight. Lbs. per cu. ft.	Mod. of elas. Lbs. per sq. in.
GRANITE:					
Little Rock, Ark	21,559	1520	2205	156.2	7,040,000
Millbridge, Me	19,917	2048	2820	....	9,800,000
Chesterfield, Va	15,350	1672	2065		
Korah, Va	23,446	1608	2662		
Exter, Cal	22,557	1853	2419		
Rockville, Minn	18,121	1327	1949	....	9,420,000
Sioux Falls, Minn	18,176	1216	2086	....	6,010,000
Troy, N. H	26,174	2169	2214	164.7	
Branford, Conn	15,707	1249	1834	161.6	6,997,000
Milford, Mass	21,235	1545	2311	162.6	5,927,000
Average	20,224	1630	2257	161.3	7,532,000
MARBLE:					
(White) Rutland, Vt	11,892	1247	1023	167.6	4,455,000
(Blue) Rutland, Vt	13,864	2057	1217	....	7,267,000
(Dark) Rutland, Vt	12,833	1759	1453	....	9,290,000
Sutherland Falls, Vt	16,156	2293	1565	....	12,580,000
(Fossil) St. Joe, Ark	10,312	1615	....	....	8,210,000
(Brown), St. Joe, Ark	12,278	1614	....	....	10,740,000
(White) De Kalb, N. Y	12,497	839	....	....	12,000,000
Marble Hill, Ga	11,505	1038	1332	167.8	5,515,000
Tate, Ga	12,425	1079	1315	168.7	4,020,000
Average	12,640	1505	1318	168.0	8,231,000
LIMESTONE:					
La Motte, Vt	14,622	1640	2173	....	14,720,000
Dodge Co., Minn	4,522	253	1135	....	
Junction Cy., Kan	3,173				
Fort Riley, Kan	....	528	1022		
Beaver, Ark	20,581	2707	1998	....	6,645,000
Mt. Vernon, Ky	7,647	1314	1705	139.1	4,000,000
Rockwood, Ala	5,957	690	978		
Bowling Gr., Ky	6,043	1058	1211	....	9,290,000
Bedford, Ind	9,918	1736	1119	....	7,160,000
Average	9,058	1241	1418	139.1	8,363,000
SANDSTONE:					
Cromwell, Conn	16,894	1872	1526	....	7,711,000
E. Long Mead., Mass	10,004	941	1199	133.8	1,582,000
Jasper, Ala	15,630	1889	2202	....	
Pike Co., Minn	12,547	868	1555		
Cabin Creek, Ark	18,468	1666	2479	....	3,900,000
Fort Smith, Ark	12,765	1473	1765	....	3,530,000
Redfield, Kan	8,027	2088	1940	....	
Oakland, Cal	11,041	1063	1626		
Coos Co., Ore	7,444	....	1248		
Olympia, Wash	12,655	2185	1643	....	3,277,000
Chuckanut, Wash	11,533	1488	1809	....	2,120,000
Tenino, Wash	6,688	495	1226	....	1,020,000
Pittsburg, Wash	19,208				
Average	12,531	1457	1685	133.8	3,306,000

all situations involving high stresses, as in the case of monolithic columns in buildings, the stone should be chosen only after tests have been made of the particular stones under consideration.

STONE MASONRY

14. Classification. Stone masonry is classed as *rubble masonry, squared stone masonry,* or *ashlar* or *cut-stone masonry.* "Rubble masonry includes all stone masonry composed of unsquared stones. It may be *uncoursed rubble,* Fig. 1, laid without any attempt at regular courses, or *coursed rubble,* Fig. 2, leveled off at specified heights to a horizontal plane."

Squared Stone Masonry. "According to the character of the face, this is classed as *quarry-faced,* Fig. 3, or as *pitch-faced,* Fig. 4. If laid in regular courses of about the same rise throughout, it is *range* work, Fig. 5. If laid in courses that are not continuous throughout the length of the wall, it is *broken range* work, Fig. 6. If not laid in courses at all, it is *random* work, Fig. 7."

Ashlar Masonry. "This is equivalent to cut-stone masonry, or masonry composed of any of the various kinds of cut stone mentioned above."

As a rule the courses are continuous, Fig. 8, but sometimes are broken by the introduction of smaller stones of the same kind and then it is called *broken ashlar,* Fig. 9.

15. Compressive Strength. The actual compressive strength of stone masonry has not been satisfactorily determined experimentally. The few tests which have been made do not form a sufficient basis for the determination of the relative strengths of the different classes of masonry, nor the relative strengths of masonry of the same class when different kinds of stone are used.

The manner of failure of masonry under compression is almost invariably by the compressive failure of the mortar, followed by lateral flow of the latter, thus setting up tensile stresses in the stone which open up longitudinal cracks.

It is obvious that the integrity or a masonry structure is destroyed by this failure of the mortar in the joints. In fact it is only with the strongest mortars (such as neat cement) laid in the thinnest possible joints that the real strength of building stone can be developed. With the common mortars as generally used the data at hand would tend to indicate a strength for stone masonry not over two-fifths of the compressive strength of the stone itself. With thick joints and lime mortars this may fall as low as one-tenth the strength of the stone.

RUBBLE

Fig. 1
UNCOURSED RUBBLE

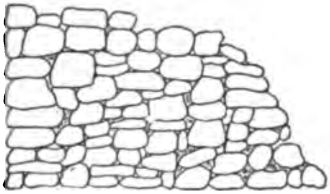
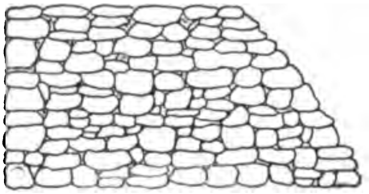
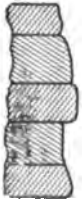


Fig. 2
COURSED RUBBLE



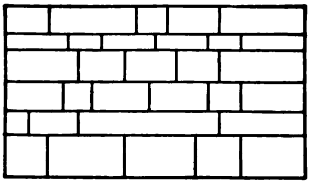
SQUARED STONE

QUARRY FACED
Fig. 3

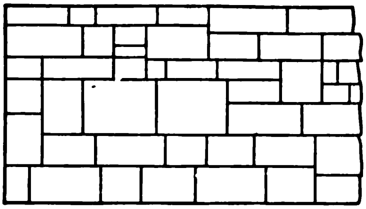


PITCH FACED
Fig. 4

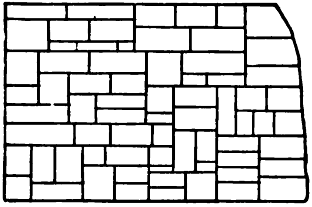
RANGE
Fig. 5



BROKEN RANGE
Fig. 6

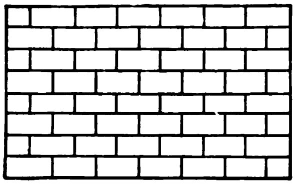


RANDOM
Fig. 7

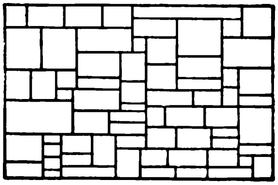


ASHLAR

ASHLAR
Fig. 8



BROKEN ASHLAR
Fig. 9



16. Allowable Loads on Stone Masonry. Conservative building laws recommend about the following values as safe pressures for the different classes of stone masonry:

ALLOWABLE LOADS ON STONE MASONRY

Kind of masonry.	Pounds sq. in.
Rubble, uncoursed, in lime mortar	60
Rubble, uncoursed, in Portland cement mortar	100
Rubble, coursed, in lime mortar	120
Rubble, coursed, in Portland cement mortar	200
Ashlar, limestone, in Portland cement mortar	400
Ashlar, granite, in Portland cement mortar	600

STONE AS ROAD METAL

17. General. In highway construction stone may appear as cut blocks or cobblestone in paved streets; as crushed stone in broken stone roads, bituminous macadam pavements, and bituminous or cement concrete pavements; as sand or gravel in dirt and gravel roads. The desirable qualities and characteristics are somewhat variable dependent upon the type of road, the severity of use and the kind of vehicle commonly passing over it.

18. Properties. As in the case of building stone the actual crushing strength is, on the whole, of but secondary importance. The special qualities most commonly noted for road building stone are toughness, resistance to wear or abrasion, and hardness. Occasionally the absorption, specific gravity and a highly specialized property known as cementing value may become factors worthy of consideration but generally they are of very minor importance.

These qualities are determined by special methods of testing which have been carefully standardized by the United States Office of Public Roads, and the American Society for Testing Materials. The standards for comparison are wholly arbitrary and in all cases require special apparatus for their determination.

Toughness is determined from a one inch cylindrical specimen one inch long. This specimen is fractured by the impact of a two kilogram hammer transmitted through a standardized plunger. The vertical drop of the hammer (1 cm. for the first impact) is increased 1 cm. for each blow. The number of blows required to produce fracture is the measure of the toughness.

Resistance to Wear or the "French Coefficient of Wear" is determined by rattling 50 pieces roughly cubical and of approximately uniform size, weighing in the aggregate approximately 5 kilograms, in a closed cylinder which rotates about an inclined axis. The loss in weight after 10,000 revolutions may be expressed as per cent but more commonly in terms of the "French Coefficient" which is 2000 divided by the total loss in grams.

Hardness is determined by pressing a one inch cylinder endwise against a revolving disc upon which is fed clean crushed quartz of standard size. A pressure of 1250 grams is maintained and 1000 revolutions constitute a test. The hardness is expressed by the relation $H = 20 - \frac{1}{3} W$ where W is the loss of weight in grams.

19. Significance of Tests. In all of the above noted tests wide variation is shown even when made by the same observer and with samples as nearly alike as it is possible to obtain. There is a tendency at the present to introduce certain modifications into the methods of testing.

Until such modifications have been made it is necessary that results of tests on road material be interpreted somewhat broadly. In general the following recommended by the Office of Public Roads may be used as a guide in the choice of available stone for road material.

Property.	Low.	Medium.	High.
Toughness	below 13	13 to 19	20 and over
French coefficient	below 8	8 to 13	14 to 20
Hardness	below 14	14 to 17	17 and over

QUALITIES OF ROCK TYPES

20. Trap. Hard, high abrasive resistance, tough, if free from fine joints and seams. (It should be noted that with the true trap rocks there are commonly associated, at least commercially, many other more or less fine grained, dark colored, igneous rocks. These are generally inferior to true trap, particularly in regard to toughness.) True trap rock may be used for all classes of modern road construction.

21. Granites and other similar coarse grained rocks are usually lacking in toughness, of moderate wear resistance, and evince great variation in hardness. In general they should not be used for road surfaces, except in the form of paving blocks, or in base courses.

22. Sandstones of the better qualities and **quartzite** are very tough, show satisfactory coefficient of wear, and are quite reasonably hard. (It should be noted that sandstone may be formed with a number of cementing materials of which iron is the most desirable, while lime and clay will produce weak and soft varieties.)

23. Limestone is somewhat variable in character, much of it is quite worthless as road material, while certain localities furnish varieties with good wear resistance and fair toughness though not very hard.

24. Shales, slates and **schists** in general are very unsatisfactory as road material. This is due in part to their foliation, which causes the rock to break into flakes.

25. Fieldstone must of a necessity be of very heterogeneous character and hence of variable characteristics. Availability and other exigencies often lead to its use, frequently resulting in very uneven wear of the road.

SECTION 4

CHAPTER I

BRICKS AND OTHER CLAY PRODUCTS

GENERAL

1. Clay Products as Structural Materials. The principal clay products used structurally are building brick, paving brick, fire brick, terra cottas, and various forms of tiles.

Brick may be made from a large number of different classes of material, the one essential being that the material be of a mineral nature and possess a considerable degree of plasticity when dampened. Common building bricks are usually made of a mixture of clay and sand (to which coal and other foreign substances are sometimes added), which is mixed and molded in various ways, after which it is dried and burnt.

Paving bricks are made primarily as a material for street pavements. Certain classes of paving bricks are largely used, however, as a substitute for building brick.

Fire bricks are of such a nature that they will withstand high temperatures. Their structural uses are largely confined to linings of flues, stacks, etc.

Terra cotta is made of selected clays in much the same way as ordinary brick. Architectural terra cotta is used for decorative effect on buildings, and terra cotta lumber and hollow blocks are used for both interior and exterior walls of buildings and as fireproofing to protect steel-work.

Tiles, made by burning various classes of clay, are used in various forms as roofing tile, wall or floor tile, drain tile, sewer pipe, etc.

2. General Classification of Bricks and Clay Products. The principal classes of bricks and other clay products which are used as building materials are included in the following classified list, in which certain subdivisions of the materials above mentioned have been made:

Building bricks.
  Common building brick.
  Face or pressed brick.
  Enameled or glazed brick.
  Ornamental brick, tapestry brick, and Roman tile.
  Hollow brick.

  - Sand-lime brick (not a clay product).
- *Paving bricks.*
- *Fire bricks.*
- *Terra cotta.*
  - Architectural.
  - Terra-cotta lumber.
  - Hollow building blocks and fireproofing.
- *Roofing, wall, and floor tiles.*
- *Drain tile and sewer pipe.*

MANUFACTURE OF BUILDING BRICK

3. Kinds of Clay. The different classes of clay from the standpoint of geological manner of formation have been discussed in Section 2 Art. 8. Of the three general classes, residual, sedimentary, and glacial clays, all are used for brick making when they possess a sufficient plasticity for molding and burn to a body of the proper hardness, but sedimentary clays are most frequently found satisfactory. The following classification of sedimentary clays is made by Ries:

CLASSIFICATION OF SEDIMENTARY CLAYS

- *Marine clays or shales.*
  - White-burning clays. Ball clays and plastic kaolins.
  - Fire clays or shales, buff burning.
  - Impure clays or shales.
    - Calcareous.
    - Non-calcareous.
- *Lacustrine clays* (deposited in lakes or swamps).
  - Fire clays or shales.
  - Impure clays or shales, red-burning.
  - Calcareous clays, usually of surface character.
- *Flood-plain clays* (usually impure and sandy).
- *Estuarine clays* (deposited in estuaries, mostly impure and finely laminated).

Marine deposits of clay often stretch for hundreds of miles with a depth of 30 feet or more. Their composition is remarkably uniform, and, except in the case of those which are too high limed or are excessively plastic, include the best clays obtainable for brick manufacture.

Lacustrine and estuarine clays occur in beds of limited extent and usually of no great depth. They may be sandy and are less advantageous for use in brick-making than are the marine clays.

Flood-plain clays are sometimes very sandy or even contain large pockets of pure sand. They are sometimes very calcareous, and cannot be advantageously used.

4. Influence of Kind of Clay upon Character of the Brick. Most clays used in brick-making contain, in addition to silicate of alumina, variable quantities of lime, magnesia, iron oxide, and alkalies. A very plastic clay is apt to shrink, crack, and warp in drying and be very hard after burning. The presence of coarse sand in suitable amounts tends to prevent shrinking and cracking in burning, but an excess of silica in the shape of sand destroys cohesiveness. Iron oxide acts as a flux and adds greatly to the hardness and strength of brick. It causes the clay to burn buff or red in color according to the amount of iron oxide present. Lime considerably in excess of iron, causes the brick to burn buff and shrink strongly as vitrification is approaching. The lime must be in a very finely divided state so that it will be completely hydrated or fluxed in the process of manufacture of the brick. The presence of lumps of unhydrated lime which become hydrated after long periods is the cause of unsightly defects on brick walls called "lime-pops." Magnesia and alkalies also act as fluxes.

HAND PROCESSES OF MANUFACTURE

5. Preparation of the Clay. A small proportion of common brick is still made by hand, and many specially molded brick made for various special purposes are made by hand methods.

The clay must first be freed from any pebbles, soil, excessive sand, etc., by washing. With the better class of clays this step is not required.

Clays not put through a wash mill sometimes require crushing to reduce them to a state in which they readily mix with water. This is usually accomplished in either a set of rolls or in an edge-runner mill. Clays which require an excessive amount of crushing are not used in hand processes..

After crushing, the clay is tempered by mixing in a moderate amount of water and then is allowed to stand for a time before the final pugging of the mix.

6. Pugging. The final reduction of the mix to a plastic mass is done in a pug-mill. At this stage it may be necessary to add sand to reduce shrinkage, or more water, the exact proportions being carefully controlled and kept uniform.

The pug-mill, Section 2 Fig. 16, is usually a horizontal cylinder provided with one or two power-driven blades. The revolving blades slice up and mix the mass till it is ejected through an opening at one end.

7. Molding. There are two common methods of hand-molding. In the first, known as *slop-molding*, the mold is dipped in water just before filling to prevent the adhesion of the clay to the mold. The workman kneads the clay into approximate shape with his hands, forces it into the mold and tamps it hard, and then strikes it even with the mold by the use of a straight-edge. The mold is not removed till the brick reaches the dryer room. This method is slow and yields many imperfectly formed bricks. The second method is called *sand-molding*, and differs from the first in that, instead of dipping the molds in water to prevent the clay from sticking, the mold is sprinkled with sand to effect the same purpose. The operation of filling the mold is practically the same as in the first method, but, owing to differences in the details of manipulation, the second method is more rapid and the bricks are usually cleaner and sharper than those produced by slop-molding. Sand-molded bricks are known as "sand-struck brick."

8. Drying. After being shaped in the mold the bricks are allowed to dry for several weeks before being fired. Artificial dryers are seldom used in connection with hand processes. Very often the drying is accomplished in the open air on racks which support the bricks in such a manner as to allow a maximum access of air and sunlight to all sides of the tiers. In order to prevent injury by rain it is desirable to cover the tiers with a light roofing of boards. For the better qualities of brick sheds containing racks must be used, or an artificial dryer installed. These sheds are permanent structures provided with a weather-tight roof, and with side walls which are either fitted with shutters or which are built of perforated bricks. Soft-mud brick and slop-molded brick often require from three to six weeks drying; stiff-mud brick and sand-molded brick are sometimes fired after less than one week on the drying racks.

9. Pressing. When hand-made brick are to be pressed the drying must be carefully watched and they must be taken to the press before becoming too dry and hard. The press used is a portable one which is operated by hand. The bricks are placed one by one in the machine between dies and compressed by a piston operated by a lever. The bricks are pressed and replaced on the rack as fast as they can be handled, the press being wheeled along between the racks as the work proceeds.

The kilns used in hand processes differ in no respect from those used for machine-made brick (Art. 14), except that the more elaborate types of kilns and especially the continuous kilns are seldom used in connection with hand molding.

MACHINE PROCESSES

10. General. Brick-making upon a large scale is now done almost entirely by machinery, from the mining of the clay by steam shovel to the molding in automatic machines and burning in semi-automatic kilns. The equipment used for the manufacture of machine-made brick varies greatly, on account of variations in the character of the raw material available, and variations in the class and quality of brick desired.

There are three general processes employed in brick manufacture: *The soft-mud process*, the *stiff-mud process*, and the *dry-press process.*

11. Soft-mud Process. The soft-mud process is practically the same as that employed in hand processes except that hand work is largely replaced by machines. The clay, unless it is found very free from pebbles and excess sand, is first cleaned in a wash-mill, after which it is tempered, coal dust or sand being added, if desired, in the tempering tanks, and then pugged in the machine which fills the molds.

The upper part of the molding machine is virtually a pug-mill which delivers the pugged mass to molds below where it is pressed into place by a plunger. The filled mold is now moved to one side and a second mold is brought into place and filled while the brick last made is being removed from its mold. The amount of pressure exerted on the clay is necessarily under constant control since variations in the stiffness of the clay make variations in pressure necessary. The machine generally uses gang-molds and so makes perhaps four or six bricks at each stroke of the plunger. The molds are usually sanded between reversals of the table which shifts the molds back and forth under the plunger.

The drying of the soft-mud machine-made brick is usually accomplished in the same manner as for hand-made brick. But artificial drying is often used.

12. Stiff-mud Process. The making of brick by the above-described methods means the incorporation in every brick of a pound or more of water which must later be dried out and driven off in the kiln. A process whereby the brick clay is only sufficiently moist to possess the requisite coherency under moderate pressure results therefore in economy of time in drying, and economy of fuel in burning.

This process requires in the first instance a clay which is not too wet. The lumps are sometimes broken up with the addition of water in a pug-mill or mixer, or the clay may even be finely disintegrated in an edge-runner mill if necessary (Section 2 Fig. 15). Usually it is pugged with or without the addition of water, either in a separate pug-mill or in the brick-making machine itself, without previous grinding.

The brick-making machine may be either of two general types, viz., the *auger type* or the *plunger type.* The auger machine consists of a closed tube of cylindrical or conical shape, in which, on the line of the axis of the tube, revolves a shaft to which is attached the auger and auger knives. The knives are so arranged as to cut and pug the clay and force it forward into the auger. The function of the auger is to compress and shape the clay and force it through the die. When the clay passes through the die it is compressed to as great an extent as it can be in its semi-plastic condition. The opening in the die is made to conform to the dimensions of either the end or the side of a brick, and a continuous bar of clay is forced through onto a long table where it is cut into sections the size of a brick. If the cross-section of the bar is the same as the end of the brick the brick are called *end-cut*, and when the section corresponds to the side of a brick they are *side-cut*. When end-cut brick are made the clay often issues from the machine in several separate streams.

The bar of clay as it issues from the die travels along the table on an endless belt which is supported on rollers. At intervals the operator throws a lever which swings downward a rigid frame across which a series of wires are tautly stretched. Thus the bar is cut into sections of either the length or the thickness of a brick. When the lever is reversed the wire frame is restored to a vertical position and the cut brick are carried away on a belt conveyor. Many types of machines are used for cutting the bar of clay into bricks, but all use wires to do the actual cutting.

The great majority of bricks made by the stiff-mud process are made in the auger type of machine. The plunger type of machine is used to some extent, however.

In the plunger type of machine the clay after pugging is forced into a closed chamber which acts as a feeder for the pressure cylinder into which it discharges, the amount discharged being subject to control. The forward motion of the plunger now compresses the clay and forces it through the die. The clay bar thus formed passes onto the cutting table and is cut by wires in the manner above described.

A few plunger machines are so devised that the clay is forced into molds instead of through a die. With this exception, all stiff-mud brick are *wire-cut brick*.

Some manufacturers of stiff-mud brick burn the brick without any intermediate drying. The practice is not a good one, however, since it is apt to cause excessive warping and cracking of the brick unless the firing is done with great care and very slowly. The average stiff-mud brick is improved by a moderate amount of drying before burning. The drying racks or dry-houses above described are sometimes used, but, since the bricks contain much less moisture and are stronger, the drying may be accelerated and artificial heat used.

The continuous tunnel dryer (Fig. 1) is most commonly used for rapid drying of green bricks. The bricks are piled on cars which move slowly through tunnels wherein they are heated either by hot air or by steam pipes. The tunnels are usually built of masonry, are 100 feet

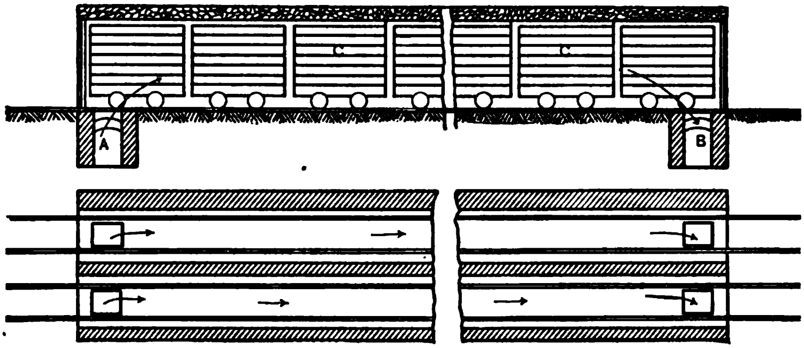


Fig. 1. — Tunnel Dryer.

or more in length, and the cars traverse the length of the tunnel in about twenty-four hours.

The usual product of the stiff-mud brick machine may be sorted into a small proportion of the face brick and a large proportion of common brick. When, however, a special face-brick is desired, the brick may be repressed in a mold under a plunger worked by a steam cylinder. Repressing reshapes the brick, rounds the corners if desired, trues it in outline, and improves its appearance. Well made stiff-mud brick are apt to be structurally injured and weakened by repressing.

13. Dry-press Process. The dry-press process is especially fitted for the handling of clays which contain not over 12 to 15 per cent moisture when they come from the bank. The clay is quarried by steam shovel and stored under cover to allow further drying, ground up in a dry pan (edge-runner), delivered to a mixer, which is simply an open pug-mill, in which it is thoroughly mixed to give a homogeneous product of about the consistency of flour, and discharged into the hopper of the brick machine.

The molding of dry-press brick is a difficult operation, the success of which is largely dependent upon the class of clay employed and the efficiency of the brick machine used. In this machine the clay is fed into the die or mold by a reciprocating charger located below the machine hopper. At each revolution of the machine the charger moves forward, and when it is directly over the molds the bottom plunger in the molds descends, allowing the molds to be filled with clay. The charger is withdrawn, the clay supply shut off, and the top and bottom plungers move toward each other in the molds, compressing the clay between them. The pressure is now relieved and then applied a second time, the compression of the clay being carried a bit farther than in the first place. The upper plunger is now withdrawn and the bottom plunger raises the brick to the level of the top of the mold. The next stroke of the plunger pushes the finished brick upon the mold table, whence it is removed to the dryers or kilns. Many machines used with dry clay are arranged to mold two, four, or more bricks at each stroke.

Dry-pressed bricks are very compact, show high compressive strength, and are well formed, but they are not generally considered to be as durable as bricks the clay for which has been tempered. They are, however, largely used as face brick. The term "pressed brick" is properly used only in referring to bricks made by the dry-clay process. The so-called pressed brick made by repressing of soft or stiff-mud brick should be called "repressed brick."

Building bricks are occasionally made by a process called the *semi-dry clay process.* It differs little in methods or equipment used from the dry-clay process.

14. Kilns and Burning. Brick kilns may be divided into two general classes, viz., *intermittent kilns,* and *continuous kilns.* Intermittent kilns may be further sub-divided into *up-draught kilns* and *down-draught kilns.* Continuous kilns are seldom used in connection with hand molding or in small plants of any type.

Up-draught Kilns. The up-draught kiln was at one time almost exclusively used in this country and is still common in small yards where the hand process is used.

The old-fashioned up-draught kiln is nothing but the green bricks themselves built into a pile about 20 to 30 feet wide, 30 to 40 feet long and perhaps 12 to 15 feet high. The sides and ends are plastered with mud to keep in the heat, and the top is covered with earth and sometimes roughly roofed.

The bricks are piled in such a way as to form a series of arched openings extending entirely across the kiln, and in these arches the fires are built.

The bricks nearest the fires are badly over-burned, sometimes to vitrification, and are called "arch brick." The bricks at the top of the kiln are under-burned, and are called "salmon brick," and only the intermediate bricks are first-class building brick.

The modern up-draught kiln has permanent sides made of 12 or 16-inch brick masonry walls, and the heat is generated in ovens outside. The flames and hot gases enter the kiln through fire passages in the walls and arches made through the brick within the walls. This type of kiln is more economical of fuel than is the early type, and yields a much larger percentage of first-class brick.

The burning of a kiln requires about a week, after which time the openings are tightly closed and the kiln allowed to cool very slowly.

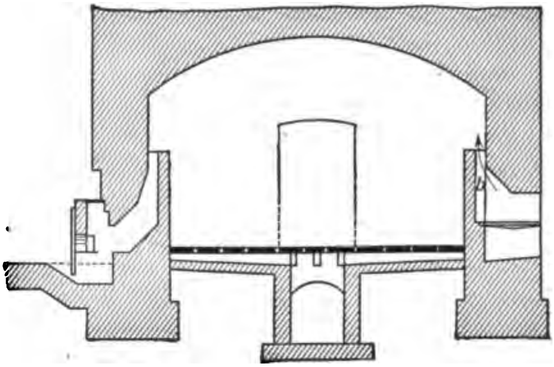


FIG. 2. — Down-draught Kiln. Vertical Section.

Down-draught Kilns. Kilns of this type require permanent walls and a tight roof. The floor has openings connecting with flues leading to a stack. Down-draught kilns are usually built in a circular or beehive shape, but are sometimes rectangular. Fig. 2 shows a circular kiln in vertical section.

Heat is generated in outside ovens and the flames and gases enter the kiln through vertical flues (*b*, Fig. 2), carried to about half the height of the kiln. The heat therefore enters the brickwork at the top and is drawn downward by the chimney draught to the flues below the floor, and thence to the chimney or stack.

The efficiency of the down-draught kiln is much higher than that of the up-draught kiln, and terra cotta and pottery, as well as brick, are burned very evenly in this type of kiln.

Continuous Kilns. Many types of continuous kilns are on the market, but all depend on practically the same principle. A number of chambers are connected in series, and also individually connected with a stack. The stack flues and the flues between chambers are provided with dampers. While one chamber is burning, the waste products of combustion are forced to traverse the whole series of charged chambers before reaching one which is open to the stack. The material is thus preheated before being fired. The flue openings are in the floor so that the down-draught principle is utilized. This type of kiln is expensive to install, but is more economical of fuel than any other kiln. The percentage of first-class brick is also high, provided that the fuel is burned on grates or in troughs, instead of in contact with the brick.

15. Sorting and Classification. Uses of Various Grades. In emptying the kiln, the bricks are commonly separated into various grades or qualities according to the degree of burning and freedom from imperfections. All bricks which show cracks or excessive kiln-marking as well as those which are badly warped must be put into an inferior class.

All of the classes of brick whose manufacture is discussed above are classed under the head of **common brick or pressed brick.** Common bricks are usually divided into three grades:

Arch or hard brick, those which, owing to their position in the kiln, have been over-burnt, are apt to be misshapen, and are used only in footings and for the "filling" of brick masonry.

Red or well-burned brick, which amount to about half the output of the up-draught kiln and constitute the best grade of brick for all general construction purposes.

Salmon or soft brick, those which have not been sufficiently burned, are too weak for use as a first-class construction material, but are used for masonry filling and unimportant work not calling for high strength or great durability.

Pressed brick or face brick are made by the dry-clay process as above noted or, using the commonly accepted meaning of the term, by repressing soft or stiff-mud process bricks. They are smooth and hard, have true surfaces and sharp angles, and can therefore be laid with a minimum thickness of mortar joint. The advantages they possess in appearance favor their use in the facing of masonry.

Glazed and enameled brick. Glazed brick are those made by coating one side of unburned common brick with a thin layer of what is called "slip," a composition of ball clay, kaolin, flint, and feldspar, and then applying a second coat of transparent glaze resembling glass. The slip gives the color to the brick, and the glaze melts upon firing the brick, and forms a smooth transparent coating over the white slip.

Enameled brick are made from a clay of peculiar character, generally containing fire-clay, and the enamel is applied either to the unburnt brick or to the finished brick. In burning, the enamel fuses and unites with the body of the brick. It does not become transparent, but gives its own color to the brick.

Enameled brick are expensive and more difficult to make than glazed brick, but the former are generally considered the more durable.

Both glazed and enameled brick are particularly adapted for use in interior finishing, lavatories, hospitals, etc.

Ornamental brick are simply common brick which have been formed in a special mold which imparts some relief design to the face. Specially selected clays may be used to impart some desired uniform color. They are made in various sizes and shapes.

Tapestry brick are made by the stiff-mud process, and subsequently have their surfaces roughened by cutting off a slice by a wire. Tapestry brick are much used as a face brick.

Roman tile are pressed or repressed brick of unusual form, their face dimensions being 12 by 1½ inches, and the depth 4 inches.

Hollow brick are common brick made by the stiff-mud process, a special die which forms hollow spaces through the length of the brick being used. This produces a light brick which is much used for interior wall facing and for partitions. When their surface is grooved to afford a hold for plaster, hollow brick are called *furring brick.*

Sand-lime brick are not made from clays, but since their uses are identical with those of ordinary building brick, their manufacture will be separately discussed at this point.

SAND-LIME BRICK

16. General. There are several classes of brick which are manufactured by combining sand and lime in proper proportions. Only one of these is important as a commercial article, however, and entitled to the name "sand-lime brick."

Sand brick are made up of a mass of sand bound together by calcium carbonate or silicate hardened by exposure in the air, or in air charged with carbon dioxide, such as the gases from a lime kiln.

Mortar brick which have simply calcium carbonate as the binding material, are really simply blocks of lime mortar hardened in air. They are structurally weak and unfit to be used as a building material.

Sand-lime brick are made from the same raw materials, but with much more care by a materially different process. The binding material is here not definitely established. The bricks are molded under pressure, and they are hardened in an atmosphere of steam under pressure.

17. The Sand. Almost any sand may be used if the process is varied to suit its properties. A comparatively pure and clean sand is, however, essential.

Experiments made in the laboratory of the Polytechnic Institute at Riga show that the binding action of lime and sand proceeds much more rapidly when the sand is very fine. From the standpoint of denseness and strength, however, a sand of such composition as to secure a minimum of voids is preferable. A composition of at least four parts of sand which is between the 20-mesh and the 100-mesh screen size to one part of sand finer than the 150-mesh has been found to give a brick of maximum compressive strength.

From the standpoint of weathering qualities it is apparent that a well-graded mixture will make a brick of lowest absorption and hence least apt to disintegrate due to weathering.

The principal impurities in sand are clay, iron oxide, mica, and feldspar. Clay has been found to have a marked influence in decreasing both the compressive and tensile strength of sand-lime bricks. Iron oxide is probably inert and the same is true of mica. More than very small percentages of mica are injurious, however, in a purely mechanical way.

18. The Lime. Either high-calcium lime or dolomitic lime may be used, but the former is preferable. The amount of lime used in practice varies from about 5 to 10 per cent.

19. Preparation of the Sand. The preliminary treatment of the sand is dependent first upon the source of the sand, and second, upon the subsequent details of manufacture. If a soft sand-stone rock is used it must first be crushed and then screened to separate out the larger particles. If the sand be obtained by dredging it must be dried, the amount of drying being dependent upon the subsequent manner of operation. If an excess of clay is present, or if it be a seashore sand contaminated with the salts of sea-water, washing and subsequent drying are required. If the sand does not contain a sufficient proportion of very fine quartz sand it is necessary to pulverize a portion of it in a tube mill or other type of fine-grinding machine and add the pulverized sand to the natural sand.

20. Preparation of the Lime. The preparation of the lime is simply a matter of hydrating or slaking it either before or after the addition of the sand. In the majority of cases the lime is slaked before mixing with the sand, the one exception being the use of a very wet sand. In this event the unslaked lime may be mixed with a portion of the wet sand and thus slaked, and the balance of the sand after being dried is added to the mix. With a moist sand the lime may be slaked to a putty before being mixed with the sand. The best method, however, consists in the use of dry sand and dry hydrated lime.

21. Mixing. The thoroughness of the mixing process is the most essential detail of the entire process. Probably the best method of thoroughly incorporating the 5 to 10 per cent of lime used with the sand and water consists in mixing the lime and sand in a tube mill and then adding water to the mix in a pug-mill. The latter delivers the mix to a bin where it is allowed to stand for some hours before being delivered to the press.

22. Pressing the Brick. Owing to the gritty character of the mix it is not possible to make wire-cut sand-lime brick. They are therefore made in a mold under pressure in the same manner that dry-clay brick are made. Pressures up to 15,000 pounds per square inch are used.

23. Hardening. The brick are not allowed to harden in air, but are hardened in closed chambers subjected to steam under a pressure of from 100 to 150 pounds per square inch. The hardening kettle used is a horizontal cylinder of steel, provided with a removable steam-tight cylinder head and tracks upon which cars carrying the brick are run into the cylinder. The time required for hardening depends upon the steam pressure used and is usually between 4 and 10 hours.

MANUFACTURE OF PAVING BRICK

24. General. The requisites for a good paving brick are that it shall be hard enough to resist the abrasive action caused by street traffic; tough, so that it will not be broken by the impact of wheels, horses' hoofs, etc.; and non-absorptive, so that it will resist weathering. Its manufacture differs from that of common brick, first, in that the selection of a suitable clay is more limited, and second, in that it must be burned at a much higher temperature, vitrification or at least incipient vitrification being required.

25. The Clay. Surface clays are generally unfit for use as paving-brick clays because, on account of their highly siliceous character, the range of temperatures between incipient and viscous vitrification is so short that only a small proportion of the kiln charge is properly burned.

Impure fire clays are used to a slight extent, but are very hard to burn properly. A pure fire clay cannot be vitrified; it is necessary, therefore, that there be present at least from 5 to 7 per cent of fluxing impurities (iron, lime, magnesia and alkalies). These clays possess one advantage in that it is usually impossible to over-burn them, and the burning need not be watched so carefully, as in the case of the surface clays and the shales.

Shales or rock clays are used for practically all paving brick made at the present time. They occur in larger bodies than either of the other classes of clays and, although the expense of crushing is increased owing to their rock nature, they are so impure that the range of vitrification is often as much as 400° C. (752° F.), making them an especially valuable material for paving-brick manufacture.

The shale banks are usually worked by steam shovel with or without blasting of the rock. Fireclays are mined in underground chambers like coal, and surface clays are usually handled by hand tools, scrapers, carts, etc.

Upon delivery at the plant, shales are crushed either in dry pans, rolls, or centrifugal disintegraters. Fireclays and surface clays are handled in the same types of disintegraters. The crushed clay is screened to remove all particles not passed by about a 20-mesh sieve, and delivered to the pug-mill where just sufficient water is added to make a stiff mud.

26. Molding and Drying. Practically all paving brick are made by the stiff-mud process above described, the machine being usually of the auger type. The size of the die is larger than in the case of building brick, since the usual size of paving brick is about 3½ inches wide by 8½ inches long and 4 inches deep. Both side-cut and end-cut brick are made.

Many paving bricks are repressed immediately after molding, the repressing being useful in making the brick more uniform in size and shape. The repressing dies are so formed that the edges of the brick are rounded off, lugs are made on the sides to separate the brick slightly when laid in the street, and the imprint of the manufacturer is placed on the brick.

Paving bricks which are simply wire cut without being repressed are usually what are called "wire-cut lug brick." They differ from ordinary wire-cut brick only in that the wire-cutting mechanism is so contrived that instead of the wires cutting plane surfaces, they cut planes which are interrupted by two high points which serve as lugs. Such bricks must be side cut.

"Hillside" brick have one of the upper edges beveled off to make a pavement less smooth.

Drying of paving brick is accomplished by the same methods as those used for ordinary stiff-mud brick.

27. Burning, Annealing and Sorting. The burning of the brick is accomplished either in the down-draught kiln or the continuous kiln. The burning requires from seven to ten days and the temperature is a bright cherry heat, whereas only a red heat is attained in burning hard building brick. The temperature required varies according to the clay used, and the proper temperature of vitrification for a given clay must not be exceeded, since it results in the brick becoming softened. At the best the brick in the lower portion of the kiln are usually kiln-marked owing to the weight of the charge above. When the brick are thoroughly burned the kiln must be tightly closed and allowed to cool down slowly for several days. Thus the brick are annealed and acquire a great deal more toughness than when quickly cooled.

The brick must be sorted in emptying the kiln. The upper courses will be very hard burned but possibly air-checked. They are excellent brick for foundations or sewers and are sometimes called sewer brick. From the zone of checked brick to within a few courses of the bottom, the brick should be No. 1 pavers; the lower courses have not been sufficiently heated to be vitrified and are classed as No. 2 pavers. These latter brick are much used as building brick, for which purpose they form a most excellent material.

With fireclay as high as 80 to 90 per cent of the kiln charge are No. 1 pavers, and with shale about 60 to 80 per cent of No. 1 pavers are obtained.

MANUFACTURE OF FIREBRICK

28. General. The manufacture of firebrick which are able to withstand the moderate heat encountered in ordinary situations such as chimneys, flues, etc., has been carried on for a great many years. It is only comparatively recently, however, that a demand has arisen for firebrick and fire blocks to be used where they must not only withstand extremely high temperatures, but must also have certain chemical properties which make them able to withstand an oxidizing or a reducing action, either of which may be encountered in one type or another of metallurgical furnace.

The principal materials from which firebrick are made are fireclay, silica rock, ganister rock, magnesia, bauxite, and chromite. The process of manufacture varies according to the class of brick and the nature of the raw materials used.

29. Acid Brick. *Fireclay Brick.* One of the most refractory materials for use in the manufacture of firebrick is ordinary fireclay, to which flint clay, burnt fireclay, sand, or other refractory material has been added to prevent undue shrinkage in drying and burning. Fireclays owe their superiority over brick clays as a refractory material to their greater purity, i.e., the absence of the fluxing impurities iron, lime, magnesia, and the alkalies. In order to afford a contrast between the composition of fireclays and typical brick clays the following table has been selected from Ries' "Economic Geology."

COMPOSITION OF FIRECLAYS AND BRICK CLAYS

	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	CaO.	MgO.	Alk.	H_2O.	CO_2.	SO_3.
Plastic fireclay	57.62	24.00	1.90	1.20	0.70	0.30	0.70	13.20	...	0.35
Flint fireclay	59.92	27.56	1.03	...	Tr.	Tr.	0.64	10.82	...	...
Brick shale	54.64	14.62	5.69	...	5.16	2.90	5.89	4.59	4.80	...
Calcar. brick clay	38.07	9.46	2.70	...	15.84	8.50	2.76	2.49	20.46	...
Blue shale clay	47.92	14.40	3.60	...	12.30	1.08	2.70	4.85	9.50	1.44

Fireclays are often mined in underground workings, and the plastic clay which is mixed with the fireclay is handled in the manner described for common brick clays. Each material is separately ground, usually in a dry pan, after which they are screened and mixed in the required proportions. The relative amounts of the two ingredients vary greatly according to the clays used, but usually approximate about equal proportions.

The mixing of the materials is accomplished either in an open mixer, or in the pug-mill, where the required amount of water is added. The plastic mass delivered from the pug-mill is usually allowed to stand for some time in order to allow the moisture to become more perfectly distributed before being sent to the molder or brick machine. A large proportion of the brick are molded by hand by a process that is practically that of slop molding. Either the stiff-mud process or the dry-clay process may be used, however. The drying of the brick is effected in the manner that would be used for ordinary clay brick made by a similar process, and the firing is done in down-draught or continuous kilns. The temperature of burning must be higher than is used with ordinary clay brick in order that there may be no further shrinkage of the brick when subjected to high temperatures in use as a furnace lining, or in any similar situation. A temperature of from 1371° C. (2500° F.) to 1927° C. (3500° F.) is required for proper burning, the lower figure applying to the lower grade of ordinary firebrick and the upper figure for the highest grade. The cooling should be rapid till the temperature is below 1371° C. (2500° F.), after which point slow cooling is required.

Silica Brick. Silica brick are made of silica sand or silica sandstone rock, mixed with a very small percentage of lime, which acts as a binding material. Silica brick made of the purest grade of materials will withstand a temperature of about 2150° C. (3900° F.), while the usual commercial article will fail at temperatures above about 2038° C. (3700° F.). They are therefore slightly less refractory than the highest grade fireclay bricks, but are superior to the ordinary run of fireclay bricks. Silica bricks can be made only of very pure materials since small percentages of the fluxing impurities materially increase fusibility. The brick are extremely hard and brittle and upon being heated expand, instead of shrinking, as clay brick do. This expansion, amounting to about 10 per cent, must be allowed for in laying the brick.

The silica rock is crushed between rolls or in a gyratory crusher and then pulverized in an edge-runner mill. In this latter mill lime is added, 1½ to 2 per cent being used, and water is mixed with the mass. Usually the lime and water are added together in the form of lime-milk. The final composition of the brick will be 96 to 97 per cent silica, 1½ to 2 per cent lime, and 1½ to 2 per cent impurities.

Usually silica brick are molded by hand, dried in dry-rooms or drying tunnels, and fired in down-draught kilns. No particular precautions are necessary in firing, the temperature required being from 1427° C. (2600° F.) to 1760° C. (3200° F.). The cooling down of the brick must be accomplished with the greatest care, however, since silica bricks are very sensitive to sudden changes in temperature.

A very high-grade silica brick is produced by the process used in the manufacture of sand-lime brick. The materials are mixed as a stiff mud, molded in a press, and hardened under steam pressure for about eight or ten hours.

Ganister Brick. Ganister brick are intermediate in grade between fireclay brick and silica brick. They are made from ganister rock, which is a dense siliceous sandstone containing about 10 per cent clay.

Ganister brick are made in a manner similar to silica brick except that lime is seldom added, since the clay forms a sufficient binder. Firing is done at about the same temperature as that required for silica brick and the cooling must be slowly and carefully accomplished.

30. Basic Brick. *Magnesia Brick, Bauxite Brick.* All of the firebricks above described are of an "acid" character, that is, being composed largely of silica, they are capable of acting as an acid material at high temperatures, and of fluxing in contact with a basic material such as lime. By decreasing the silica content and increasing the alumina content the material may be rendered "basic" in character.

Materials which are used for making basic bricks are principally "bauxite" and "magnesia." Bauxite brick are made by grinding bauxite (85 per cent or more Al_2O_3) in an edge-runner, mixing with about 25 per cent clay in a pug-mill where water is added, and molding by hand or by the stiff-mud machine. Burning is done at a temperature of about 1538° C. (2800° F.). The composition of bauxite brick is about 70 per cent alumina, 16 to 18 per cent silica, and 12 to 14 per cent ferric oxide. Shrinkage upon heating is excessive, and the bricks are structurally very weak.

Magnesia brick are made from a mixture of caustic magnesia (obtained by burning magnesite in a lime kiln) and sintered magnesia which contains a small percentage of ferric oxide to act as a flux. Dolomite (double carbonate of lime and magnesia) is sometimes used to make magnesia brick, but is inferior to a mixture of sintered and lightly burnt magnesia.

The materials are ground in an edge-runner mill, water is added in a mixer or pug-mill, and the bricks are molded under a heavy press. Drying must be carefully carried out in drying houses or drying tunnels and firing is accomplished in down-draught kilns or in gas-fired kilns at a temperature of from 1816° C. (3300° F.) to 1950° C. (3540° F.). The shrinkage of magnesia brick is irregular and excessive.

Magnesia and bauxite bricks have a remarkable power of resisting the corrosive action of slag and limestone at high temperatures, but are extremely sensitive to the action of silica and acids generally, and both are very weak structurally. They are used in the lining of basic steel furnaces, in lead smelters, in cement kilns, etc.

31. Neutral Firebrick. Chromite (chrome iron ore) is principally used for the manufacture of a refractory brick, which is practically "neutral." Chrome brick are used in metallurgical furnaces to separate basic and acid brick linings, when the former is used for the lining of the melting chamber in contact with a basic charge and the latter used for the top arches, where greater mechanical strength is needed. Chromite used alone is almost without binding power, and is therefore usually mixed with fireclay or bauxite in such a proportion that the bricks contain about 50 per cent chromium oxide, 30 per cent ferrous oxide, and 20 per cent alumina and silica.

Chrome brick are made by crushing the materials in edge-runner mills and molding under heavy pressure, as in the case of silica bricks. The firing temperature is about 1650° C. (3000° F.).

TERRA COTTA

32. General. Terra cotta is composed of practically the same material as brick, but requires a carefully selected, finely divided homogeneous clay which burns to a desirable color with a slight natural glaze.

33. Architectural Terra Cotta. Terra Cotta Lumber, Building Blocks, and Fireproofing. Usually no single clay is used in the production of terra cotta, but each shade and tint requires the mingling of different clays. Fire clays are universally used for the making of architectural terra cotta.

The clays after delivery at the factory are separately ground in wash-mills or edge-runner mills, mixed with grit and water in pug-mills and separately deposited in layers or strata. As many as ten or twelve strata are thus piled up, and from this mass perpendicular cuts are taken and the whole mixed together in a pug-mill into a plastic mass.

The subsequent manner of molding depends largely upon the character of the ware being made. *Terra cotta,* used for architectural purposes, is usually made by hand molding in plaster casts. Intricate designs are modeled without a mold and green casts are often further carved by hand before being dried and burnt. After drying and before burning a coating of "slip" is applied to the ware. This slip is made up of clay, feldspar, flint, etc., is opaque, and imparts the color desired for the finished product. Either a dull or a bright glazed finish may be procured.

Burning is done with extreme care to prevent either distortion or discoloration by flames or gases. Special kilns in which the ware does not come in contact with the gases are commonly used. Very elaborate designs of high artistic merit are sometimes executed. It is not practicable to burn terra cotta in very large units, so it is often necessary to make a complete design of many comparatively small sections.

Terra cotta blocks or terra cotta lumber is an entirely different material, made for strictly structural purposes and not at all for decorative effect, being always covered by plaster or mortar.

The raw materials used for terra cotta lumber are terra cotta clays and finely cut straw or sawdust. The materials are thoroughly mixed (after grinding) in a mixer or pug-mill to form a stiff mud, which is thereupon forced through a die by a plunger-type machine. Practically all terra cotta lumber is made of hollow construction, with walls about 1 inch thick, and with partition walls about $\frac{3}{4}$ inch thick.

The blocks are wire cut, as in the case of ordinary stiff-mud bricks, and are carefully dried before firing. Firing is usually done in a down-draught kiln and especial care is required in stacking up the ware in such a manner as to prevent distortion and unequal heating. The temperature of burning is sufficient to burn out all the straw or sawdust incorporated in the mix, and leaves a very light and porous material which is soft enough to be cut with a saw and into which nails or screws may be driven with ease.

Hollow building blocks and fireproofing are the same thing as terra cotta lumber except that no straw or sawdust has been incorporated with the clay and the burning is carried to a higher temperature, almost to vitrification. They are therefore much harder than terra cotta lumber and are not porous, but resemble ordinary hard-burned brick.

Hollow building blocks are made in the same shapes as terra cotta lumber and have the same uses. Both are used extensively as a fireproof material for constructing exterior and partition walls, ceilings, floor arches, furring for outside walls, roof sheathings, and jackets around beams and columns of steel-framed buildings.

ROOFING, WALL, AND FLOOR TILE

34. Roofing Tile. Roofing tile must be hard, strong, and of low absorption. They are made by a process similar to that employed for repressed stiff-mud brick, the blanks being formed by an auger machine and subsequently repressed. Shingle tile are laid like slate, being perfectly flat; mission style tile are, in a measure, interlocking, being segments of hollow cones; and Spanish tile are distinctly interlocking. The two latter forms are made by repressing slabs of green clay. The clay is selected with greater care than in the case of ordinary brick, and burning is done at a sufficiently high temperature to insure hardness, strength and low absorption.

35. Wall Tile. Wall tile are of two general types according to the process employed in making them — "dust-pressed" tile and "plastic" tile. The clay used in making dust-pressed tile may be a fireclay, or even a red-burning shale clay, if artificial coloring is to be used, but if a white body is required, as is usual, a mixture of white clays, feldspar, flint, etc., is employed. These materials after grinding and mixing are made up into a thin cream which is strained through a silk screen. The water is then drained or squeezed out and the material is ready to be molded if the plastic process be used. For dust-pressed tile this material is dried, crushed to powder, moistened slightly by steam, and stored until used.

Molding is done in a dry press and any desired relief pattern is imprinted by the moving plunger of the press. The ware is now placed in fireclay boxes in which it is burned out of contact with the flames. After burning, a transparent or opaque glaze is applied, coloring matter being introduced if desired. A second firing is now required to fuse the glaze. Either a bright or a dull glaze is obtained by proper selection and application of the glaze materials.

Plastic tile are made in practically the same manner as "dust-pressed" tile, except that a mixture of soft clay and powdered burnt clay is used, and the molding is done immediately after mixing and tempering. Molding is done by hand in plaster molds which may or may not impart a design to the face. In the latter case the tile may be removed from the mold when partly dry and a design modeled by hand. Sometimes plastic tile are not glazed, and in that event no second firing is required. Most wall tile are dust-pressed tile.

36. Floor Tile. Floor tile are dry-pressed from the same materials as wall tile and the process employed is practically the same. Fireclays and red-burning clays are most commonly used, however, and if white-burning materials are used coloring matter (metallic oxides) is usually introduced. No glaze is used and only one firing is necessary.

DRAIN TILE AND SEWER PIPE

37. Drain Tile. Drain tile are made from a red-burning clay or mixture of clays of the character of those used in making terra cotta lumber. The clay is handled by the stiff-mud process, issuing from a special die as a hollow cylinder, which is cut to convenient lengths by wires.

Burning is conducted at temperatures compatible with the production of a very porous product, which possesses a considerable degree of mechanical strength, but is not vitrified or glazed.

38. Sewer Pipe. Sewer pipe is not intended to be porous or absorptive like drain tile, but on the contrary is made from clays which will form a very non-porous product of low absorption. The stiff-mud process of mixing and molding is used whether the pipes are fitted with socket ends or not. Special shapes, such as elbows, Ys, and Ts, are made by joining parts of green pipe with slip clay.

After drying in steam chambers the ware is burned in down-draught kilns. A special glaze called "salt glaze" is imparted to all surfaces of the pipe by throwing common salt into the kiln fires after a temperature of about 1150° C. (2102° F.), has been attained. The sodium vapors freed by heat pass through the kiln, and by combination with the clay form a dense hard glaze, which renders the pipe practically non-absorptive.

Sewer pipes are intended exclusively for use as conductors of water, sewage, etc., and are laid with tight cement joints. They therefore do not take up and carry off the water in wet soil as drain tiles do.

PROPERTIES OF BRICKS

39. Crushing Strength. Since the strength of brick masonry is only a fraction of the strength of the brick, the compressive strength of individual bricks is of only relative value in that it affords a basis of comparison between different kinds of brick.

The average compressive strength of good building brick is about 4000 pounds per square inch; of pressed brick about 8000 pounds per square inch; of sand-lime brick 3000 to 4000 pounds per square inch; of paving brick 10,000 pounds per square inch; of fireclay brick 3000 to 6000 pounds per square inch; of terra cotta blocks, 4000 pounds per square inch; and of architectural terra cotta 3000 pounds per square inch.

40. Absorption. The absorption of water by brick is often taken to be an important criterion of its probable durability. The freezing of water which fills the pores of brick will constitute a great disintegrating agency, but the importance of this factor is probably overestimated. Bricks are seldom injured by frost for the reason that water does not fill the pores completely and hence is able to expand upon freezing without exerting a great disruptive force.

Tests of absorptive power of bricks are usually made to extend over so short a period that the results are apt to be misleading. The rate of absorption of bricks varies greatly, and therefore the usual forty-eight-hour test will sometimes show practically the ultimate absorptive power of a brick, while in other cases only a fraction of the ultimate absorption is shown.

In general the absorption shown by common building brick in a forty-eight-hour immersion test is from 12 to 18 per cent of the weight of the dry brick. For pressed or face brick the absorption is about 6 to 12 per cent; for sand-lime brick it is 12 to 15 per cent; for paving brick, 1 to 3 per cent; for fireclay brick, 8 to 12 per cent; and for unglazed building blocks of terra cotta, 10 to 15 per cent.

41. Transverse Strength. The transverse strength of bricks is one of the best indications of quality, not because bricks are often subjected to severe tests of their transverse strength in masonry, but because tests are easily made and an indication of their toughness is afforded. An indication of their approximate tensile strength is also obtained since the modulus of rupture bears a fairly close relationship to tensile strength. Experiments and experience show that the failure of brick masonry under compressive stress is really by failure and subsequent lateral flow of the mortar, thereby introducing tensile stresses in the bricks and causing cracks to open up in the masonry. The fractured surface of a brick also affords a valuable indication of the care with which the materials have been ground and mixed, and the degree of burning is made evident to an experienced observer who is familiar with the normal appearance of the bricks under examination.

The modulus of rupture of common building bricks varies from about 500 pounds per square inch to about 1000 pounds per square inch; pressed bricks, 600 to 1200 pounds per square inch; sand-lime bricks, 300 to 600 pounds per square inch; paving bricks, 1500 to 2500 pounds per square inch; fireclay bricks, 300 to 600 pounds per square inch; and unglazed terra cotta building blocks, 500 to 1000 pounds per square inch.

42. Shearing Strength. The shearing strength of bricks as shown by tests is a property of little practical importance, chiefly because it is almost impossible to make the best results really show actual shearing strength. All methods of testing which have been devised are more or less subject to the same objection, i.e., the shearing stress is not acting alone, but bending is introduced, thus bringing tension and compression into play as well as shear.

Tests made at the Watertown Arsenal indicate that the shearing strength of common bricks is about 1000 to 1500 pounds per square inch; pressed bricks, 800 to 1200 pounds per square inch; sand-lime bricks, 500 to 1000 pounds per square inch; paving bricks, 1200 to 1800 pounds per square inch; and fireclay bricks, 500 to 1000 pounds per square inch.

43. Modulus of Elasticity. The modulus of elasticity of bricks is not a constant for any considerable range of loading. The elastic properties as shown by the stress-strain curve for a compressive test are quite similar to those of concrete and mortars. For ranges of loading not exceeding one-fourth of the compressive strength the modulus of elasticity of common bricks is about 1,500,000 to 2,500,000 pounds per square inch; pressed bricks, 2,000,000 to 3,000,000 pounds per square inch; sand-lime bricks, 800,000 to 1,200,000 pounds per square inch; and paving bricks, 4,000,000 to 8,000,000 pounds per square inch.

Building bricks are classified by the Am. Soc. for Testing Materials, according to the results of the physical tests, as "vitrified, hard, medium, and soft."

CLASSIFICATION OF BRICKS

Name of grade.	Absorption limits, per cent.		Compressive strength (on edge), lb. per sq. in.		Modulus of rupture, lb. per sq. in.	
	Mean of 5 tests.	Individual maximum.	Mean of 5 tests.	Individual minimum.	Mean of 5 tests.	Individual minimum.
Vitrified Brick..	5 or less	6.0	5000 or over	4000	1200 or over	800
Hard Brick.....	5 to 12	15.0	3500 or over	2500	600 or over	400
Medium Brick..	12 to 20	24.0	2000 or over	1500	450 or over	300
Soft Brick......	20 or over	No limit	1000 or over	800	300 or over	200

"The standing of any set of bricks shall be determined by that one of the three requirements in which it is lowest."

Paving bricks are usually subjected to a "Rattler" test. In this test a charge of ten bricks of "block size," is placed in a "Standard Rattler," with an abrasive charge made up of 10 cast-iron balls 3¾ inches in diameter and weighing approximately 7½ pounds each and a sufficient number of cast-iron balls 1⅞ inches in diameter, weighing approximately 0.95 pound, to bring the total weight of the charge between 245 and 260 pounds.

The rattler is rotated at a uniform rate, between 29.5 and 30.5 revolutions per minute, for 1800 revolutions. The loss in weight is calculated in per cent of the initial weight of the brick.

The percentage of loss is not definitely standardized, but the following table shows what may be expected.

	General average loss, per cent.	Maximum permissible loss, per cent.
For bricks suitable for heavy traffic...............	22	24
For bricks suitable for medium traffic..............	24	26
For bricks suitable for light traffic.................	26	28

A well made paving block will show very much less wear than suggested by the above table.

BRICK MASONRY

44. General. Brick masonry was at one time considered as an inferior substitute for stone masonry. At the present time, however, brick masonry built with bricks made by modern processes from carefully chosen raw materials, and with the aid of elaborate plant equipment, will for many purposes and situations equal or excel most stone masonry. Brick masonry is usually cheaper than stone, it is more easily built, is a better fire resistant, and compares well as regards durability with the best stone masonry.

45. The Mortar and the Joints. Lime mortar is used in building a great proportion of the brick masonry constructed in this country. The slower setting magnesian or dolomitic limes are generally preferred for bricklaying on account of the fact that the rapidity of laying is increased by their choice in preference to high-calcium limes. Portland cement is generally added to lime mortar to secure greater strength.

The proportions commonly used in lime mortars are either one part lime or two parts sand, or, more commonly, one part lime to three parts sand.

Ordinary lime mortar hardens very slowly and the gain in strength is too slow when high walls are built rapidly. For such construction natural cement or Portland cement should constitute a portion of the mortar or better still, a Portland cement mortar may be used altogether.

For all construction below grade, or in any situation where moisture is often encountered, also in heavily stressed brick masonry in piers, arches, etc., cement mortar should always be used instead of lime mortar.

All brick should be laid with the minimum thickness of joints consistent with proper bedding. Common bricks are usually somewhat rough and uneven, but should be laid with joints from $\frac{3}{16}$ to $\frac{3}{8}$ inch in thickness. It is commonly specified that the height of eight courses of brick masonry shall not exceed the height of eight bricks laid dry by more than 2 inches.

Pressed brick, being usually smooth and true, are laid with joints not exceeding $\frac{1}{8}$ or $\frac{3}{16}$ inch in thickness.

46. Bond. Bond in brickwork is the arrangement of the bricks in courses resorted to for the purpose of tying together all parts of walls more than one brick in thickness by the action of the weight of the overlying masonry. The commonly adopted bonds for laying brick masonry are *Common bond, English bond,* and *Flemish bond.*

In common bond, Fig. 3, all of the outside brick are laid as stretchers for from four to six courses, and then a course of headers is placed. This type of bond is more generally used than any other in this country.

In English bond, Fig. 4, heading and stretching courses alternate. This is the strongest type of bond, but has not a pleasing appearance.

In Flemish bond, Fig. 5, headers and stretchers alternate in each course, each header being centrally placed with respect to a stretcher in the course below. This is a strong bond, but requires cutting brick for each course at corners.

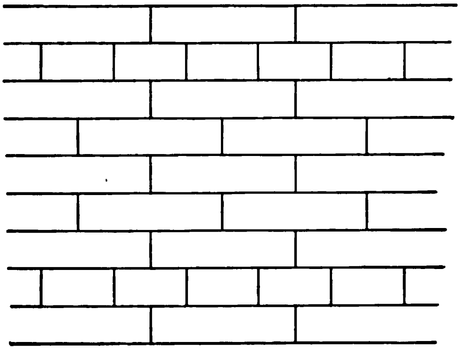


Fig. 3. — Common Bond of Brickwork.

47. Laying the Brick. Mortar, unless very wet, does not adhere to dry brick nor set properly, for the reason that the water in the mortar is absorbed by the bricks. All bricks should therefore be wet before being laid. This provision is one of great importance, but is a very difficult one to enforce since it makes a material difference in the amount of labor involved. It is difficult to lay pressed bricks dry, so there is not usually so much difficulty encountered on this score in the case of pressed brick as in the case of common brick.

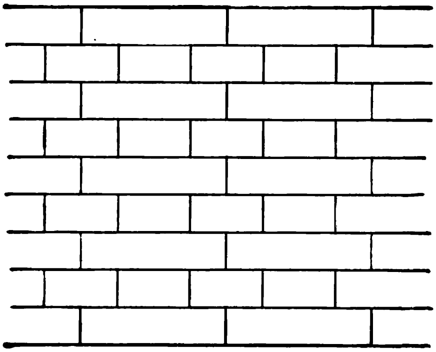


Fig. 4. — English Bond of Brickwork.

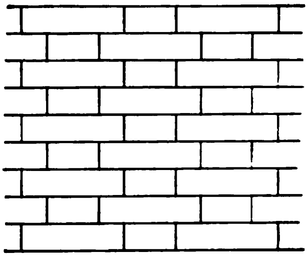


Fig. 5. — Flemish Bond of Brickwork.

After several courses of brick have been placed the joints are "struck" on the face side of the wall by means of the point of the trowel held obliquely

STRENGTH OF BRICK MASONRY

48. General. The appearance and durability of brick masonry is usually of greater importance than the actual crushing strength. In piers, however, and occasionally in arches and in the lower portion of the walls of high buildings built without a steel or concrete frame, the stresses encountered may be sufficiently high to make the crushing strength of the brick work an important consideration.

The strength of brick masonry is always much more a function of the mortar used, the bond, and the workmanship than a function of the strength of the individual bricks. Where high stresses are encountered cement mortar must invariably be used, and this is particularly true when a heavy load must be carried within a short time after the masonry is laid.

49. Strength of Brick Masonry Shown by Tests. The tests quoted below comprise a summary of tests of twenty-four brick piers about 12 inches square and 8 feet high made at the Watertown Arsenal.

These tests show the importance of using cement mortar in preference to lime mortar where strength is an important consideration. The strength of the 1 : 3 cement mortar masonry is approximately twice the strength of the lime mortar masonry, while there is little gained by the use of neat cement instead of 1 : 3 cement mortar except in the cases of the piers built with the highest quality bricks where the mortar of neat cement develops a greater proportion of the strength of the bricks

CRUSHING STRENGTH OF BRICK PIERS

WATERTOWN ARSENAL TESTS, 1904

Age 6 months

Description of brick.	Compress. strength. Lbs. per sq. in.			Per cent of the ave. crush. strength of brick.		
	Neat Port.	1 Port., 3 Sand.	1 Lime, 3 Sand.	Neat Port.	1 Port., 3 Sand.	1 Lime, 3 Sand.
FACE BRICK						
Dry pressed face brick	2880*	2400	1517	26	21	13
Re-pressed mud brick	1925	1670	1260	28	25	19
COMMON BRICK						
Wire-cut stiff-mud brick	4021	2410*	1420	31	19	11
Hard sand-struck brick	4700*	1800*	994	42	16	9
Hard sand-struck brick	1969	1800	733	44	40	16
Hard sand-struck brick	1400	1411	718	24	24	12
Light-hard sand-struck brick	1510*	1519	732	23	23	11
Light-hard sand-struck brick	1061	1224	465*	20	23	9

* Tested at age of 1 month.

SECTION 5

CHAPTER I

PIG IRON

1. Historical. The ferrous metals comprise three general classes of material, cast iron, wrought iron and steel. All of these are produced artificially by the reduction of iron ores and subsequent treatment of the pig iron by various metallurgical processes. Cast iron, wrought iron, and steel are distinctly different materials, judged by their comparative physical properties, in spite of the fact that metallic iron is present in all to the extent of over 90 per cent.

Ores of iron are all essentially oxides of iron, adulterated with varying amounts of earthy material. Many years ago it was discovered that metallic iron could be produced by heating iron ore in charcoal fires, the oxygen being removed by the charcoal, leaving metallic iron in a pasty condition. The primitive method of burning ore in heaps over a charcoal fire gradually developed into the Catalan forge process, by which wrought iron and, more rarely, steel was produced in many parts of the world for centuries.

The Catalan forge in its early form was a hole in the ground lined with masonry. This was filled with charcoal and ore, either mixed or deposited in vertical layers, and an air blast, delivered through a downward inclined tuyère which projected into the mass, supplied the necessary oxygen for combustion of the fuel.

The temperature acquired is not sufficient to melt the iron, but will fuse the slag, which may then be tapped off, and the iron withdrawn as a pasty mass. If the tuyère be given a lesser incline and the process be continued for a longer time, the temperature attained is sufficient to promote the combination of a certain amount of carbon of the fuel with iron, thereby producing steel.

Cast iron was never produced in the Catalan forge or other early form of device for reducing iron from the ore, because the temperature attained was never sufficient to melt the iron and effect the combination of iron with the 3 or 4 per cent of carbon which is primarily responsible for the structural and physical characteristics which distinguish cast iron from wrought iron and steel.

Pig iron was not produced until the blast furnace process of ore reduction was developed in comparatively modern times.

2. Iron and Steel in Construction. From the standpoint of the economist the iron and steel industry is by far the most important and valuable one in existence. The world's production of iron and steel represents a greater proportion of our manufacturing wealth than that of any other industry, and probably no other factor has contributed so much to the development of all arts and industries as has the progress made in the manufacture of better and cheaper iron and steel.

Cast iron is made so easily by a simple process of remelting pig iron and casting in molds, that it is produced in practically every city of industrial importance in the civilized world. Its strictly structural uses are somewhat limited, owing to the greater adaptability of wrought iron and steel to structural needs. As a material of construction in general, however, and especially as a material for use in construction of machines, implements, etc., it finds countless applications which cannot be as cheaply and satisfactorily served by any other material.

Wrought iron has always been an important material in many arts and industries. Until the development of cheap methods of steel making in the latter half of the nineteenth century, it was the principal metallic structural material.

Steel assumed its present place as the most important metal for general construction purposes with the development of the Bessemer process of steel making following its invention in 1855. Prior to this time steel had been produced only by comparatively slow and expensive methods, which made impossible any real competition with the relatively cheap wrought iron. In recent years open-hearth process steel has been replacing Bessemer steel.

Pig iron has no uses in construction, but is the raw form of iron from which wrought iron and steel as well as cast iron are made.

3. General Classification of Iron and Steel. Iron products may be grouped under the following heads:

Pig iron, the product obtained by the reduction of iron ores in the blast furnace. Carbon is present in amounts not usually below 2.5 per cent nor above 4.5 per cent. It is cast as it flows directly from the blast furnace into rough bars called "pigs."

Cast iron, remelted pig iron after being cast or about to be cast in final form. It does not necessarily differ from the pig in composition, and is regarded by the metallurgist as the same thing as pig iron. It is not malleable at any temperature.

Malleable cast iron, a form of cast iron which by a special annealing treatment after casting in final form has been rendered malleable or semi-malleable.

Wrought iron, a form of iron which is aggregated from pasty particles without subsequent fusion. Wrought iron contains slag enclosures, and is initially malleable, but normally possesses so little carbon that it will not harden when rapidly cooled.

Steel, iron which has been cast from a molten mass, whose composition is such that it is malleable at least in some one range of temperature, and which may or may not harden upon sudden cooling. Steel which owes its distinctive properties chiefly to carbon is called *carbon steel.* Steels whose distinctive properties are due chiefly to the presence of elements other than carbon are called *alloy steels.*

THE RAW MATERIALS OF THE IRON INDUSTRY

4. Ores of Iron. Ores of iron consist essentially of compounds of iron, usually oxides, mixed with "gangue" (silica, clay, etc.), and those of commercial importance contain from 25 to 70 per cent metallic iron.

Iron is extracted from ores by a process known as "smelting," which consists primarily in the heating of the ore to a high temperature under strongly reducing conditions in the presence of a flux. The reducing agent serves to remove the oxygen from the oxides of iron, leaving metallic iron together with such elements as carbon, silicon, manganese, phosphorus, and sulphur, which are invariably present either in the ore or in the fuel used in melting. The flux, usually limestone, combines with the gangue of the ore and the ash of the fuel, producing a fusible slag which may be separated from the metallic iron. The forms of iron ore of greatest commercial importance are *hematite*, *limonite*, *magnetite*, and *iron carbonate.*

5. Hematite. Hematite, sometimes called "red hematite" or "red iron ore," is anhydrous ferric oxide, Fe_2O_3, containing when pure 70 per cent iron. It varies from black to brick red in color, is usually very hard and heavy, but often occurs as an earthy ore which is cheaply handled. Hematite is almost entirely non-magnetic, and when pure is almost identical in appearance and composition with ordinary deep-red iron rust.

6. Limonite. Limonite, also called "brown iron ore," or "bog iron ore," is hydrated ferric oxide, $Fe_2O_3 + [n]H_2O$, containing about 60 per cent iron. It differs in composition from red hematite only in that it contains about 14.5 per cent chemically combined water. It is softer than red hematite, lighter, and occurs usually in massive form. A familiar form of limonite is the newly formed fresh yellow rust on iron.

7. Magnetite. Magnetite is the magnetic oxide of iron, Fe_3O_4, containing when pure 72.4 per cent iron. It is a hard black mineral occurring in granulated or massive structure. It is almost as magnetic as pure iron and very heavy. It is identical in composition with the black mill scale which forms on iron at temperatures above redness.

8. Iron Carbonate. Iron carbonate, commonly called "siderite" or "spathic iron ore," $FeCO_3$, contains when pure 48.3 per cent iron.

It changes to limonite and hematite on weathering. It is rarely used as an ore in its raw state, but is subjected to a preliminary calcination to remove the CO_2.

9. Ore Mining and Transportation. The manner of mining adopted depends to a great extent upon the physical condition of the ores. Many of the deposits of hematite ore in the Lake Superior district, are so soft and finely divided that they are very easily and cheaply worked by steam shovels. Others in the same district are hard and dense, and must be drilled and blasted. These rock ores are more expensively mined than the soft ores, but, the use of a certain proportion of rock ore with the earthy ore is indispensable to the successful operation of the blast furnace.

The limonites are always rather soft; the magnetites, on the other hand, are usually very hard and dense and are necessarily mined or quarried by the use of explosives and crushed before smelting.

Iron ores and the proper fuel for smelting are not often found in the same locality, therefore one of the great problems in the iron industry is the bringing of these two raw materials together in the most efficient manner.

10. Special Preliminary Treatment of Ores. Practically all of the hematite is charged into the furnace without any preliminary treatment. Some ores, however, behave more satisfactorily in the furnace after having been subjected to one or the other of the following preliminary processes.

Calcination is resorted to for the purpose of removing water from limonites or hydrous ores; removing CO_2 from carbonates; oxidizing a portion of the gangue of dense ores, particularly magnetites, thereby rendering them more accessible to the furnace gases; or rendering the ore magnetic to facilitate subsequent magnetic concentration. The calcination is usually accomplished in vertical furnaces resembling a mixed feed type lime kiln. The fuel is charged with the ore at the top and the temperature is controlled by regulation of the air supply.

Roasting is for the purpose of removing sulphur from ores. The sulphur is present as pyrite, FeS_2, which is decomposed at a moderate heat, liberating S and forming FeS. The FeS is oxidized by air to form ferrous sulphate, $FeSO_4$, and further heating decomposes the sulphate, forming ferric oxide, Fe_2O_3, with the liberation of sulphur dioxide and oxygen:

Roasting is accomplished either in large cylindrical kilns, the fuel being mixed and charged with the ore at the top or in a gas-fired kiln which consists of an annular brick-lined chamber surrounding a central cylindrical flue.

Concentration of ores is employed occasionally for the purpose of freeing the ore of a part of the gangue, and for enriching the ore before smelting. Wet concentration is sometimes used to remove clay, loam, etc., by a simple process of washing. Another method of wet concentration is by the use of jigs which separate pebbles and sand from the ore by agitation of perforated trays set in tanks of water.

Dry concentration is usually accomplished by some type of magnetic separator. If the ore is not already magnetic it is magnetized by preliminary calcination. It is then crushed and passed in a thin layer before strong magnets, the magnetic portion being thus attracted away from the non-magnetic.

11. Grades of Ore. Ores of iron are divided into two main classes known as *Bessemer ores* and *non-Bessemer ores*. This division is due to the fact that acid Bessemer steel must contain less than 0.1 per cent phosphorus, and neither the blast furnace reduction of the ore nor the acid Bessemer steel process is able to reduce the phosphorus content. All ores in which the phosphorus content does not exceed one-thousandth part of the iron content are therefore classed as Bessemer ores, and all ores carrying a higher percentage of phosphorus as non-Bessemer ores.

12. The Flux. The function of the flux is to provide a fusible slag in which the non-metallic portion of the ore may be carried off. The exact character and amount of the flux needed will depend upon the composition of the ore and fuel used, and the character of pig iron required. In general it may be said that a basic flux is required for acid gangues (high in silica, alumina, etc.), while an acid flux may be required where the gangue is basic (high in lime, magnesia, or alkaline matter). As a rule gangues are acid in character and therefore the fluxes are usually basic in character.

The flux serves another purpose, besides taking care of the gangue and ash. The sulphur in the charge, whether in the ore or in the fuel, combines with the lime of the flux, forming calcic sulphide, which is removed in the slag.

13. Fluxes Used. The most common form of basic flux is limestone. Limestone used as a flux should be very pure, since the presence of acid impurities greatly impairs its efficiency in fluxing the silica, alumina, etc., in the gangue. At least 95 per cent pure $CaCO_3$ is desirable.

Pure or high calcium limestones are not always available, and magnesian or dolomitic limestones are sometimes used. The replacement of a considerable part of the calcium by magnesium does not appear to appreciably impair the efficiency of the flux.

14. The Fuel. The fuel used in a blast furnace must serve as a reducing agent as well as a source of heat. The fuel requirements from the standpoint of heat required always exceed the requirements for reduction, and therefore only its thermal value need be considered in this connection.

The rapidity of melting attained in the furnace is dependent upon the rapidity of heat production, which, in turn, is dependent upon the rapidity of oxidation of the carbon of the fuel by the oxygen of the air. It is therefore desirable that a fuel, in addition to having a high calorific value, have a porous rather than a dense structure, thereby affording additional surface to the action of the oxygen. It is further necessary that it possess sufficient firmness while being heated so that it will not fill up the interstices of the charge, thereby impeding the flow of the gases.

All solid fuels consist of a combustible portion, carbon and hydrocarbons, which combine with oxygen to form gases, and an incombustible portion which remains as a solid residue called ash, and must be fluxed from the furnace.

Three classes of solid fuel have been used in the blast furnace; coal, coke, and charcoal. From the standpoint of structure and accessibility to oxidation charcoal surpasses coke and coke surpasses coal. From the standpoint of firmness coke stands first and charcoal is least desirable. Most of the hard, well-made cokes withstand the pressure of the charge very well. Bituminous coals melt down during heating, and anthracites under similar circumstances are apt to splinter into fine particles.

Charcoal is the purest of the solid fuels and has the least ash. Anthracite coal is less pure than charcoal and has much more ash; it is, however, much purer than coke and has very much less ash.

Each type of fuel has its advantages and all are used.

15. Coal. Anthracite coal is the only natural fuel which can be successfully used in the blast furnace without preparation. It contains very little volatile matter, the fixed carbon amounts to about 90 per cent, it is ignited with difficulty, and burns slowly. It becomes broken up very finely upon heating.

Bituminous coals have been used in blast furnaces abroad, but, because of the above indicated character of the American bituminous coals, they have never been successfully used.

16. Coke. Coke is the solid residue obtained by the distillation of certain grades of bituminous coals called "coking coals." A coking coal when heated out of contact with air to certain temperatures swells, becomes pasty, and emits bubbles of volatile gases, chiefly hydrocarbons, leaving a residue of fixed carbon, together with the ash, the phosphorus, the sulphur, etc. The weight of the coke is usually about two-thirds that of the coal used.

17. Charcoal. Charcoal is the fixed carbonaceous residue obtained by heating wood without contact of air, the volatile gases being driven off. Charcoal possesses almost the original bulk of the wood used, but is very light and very porous. It is fragile, but will withstand fairly heavy steady pressure. The ash content is very low (less than 3 per cent). Those charcoals made of soft woods at low temperatures ignite most readily, and those made of hard woods at higher temperatures ignite with difficulty.

18. Coke Manufacture. Coke is manufactured by either of two general processes. The older method produces *beehive coke,* so-called because of the shape of the oven used. The beehive oven is a circular dome-shaped structure built of brick about 12 feet in diameter and 7 feet high. Two openings are provided in the masonry, one in the crown used for charging, the other a larger opening left at the base for the purpose of withdrawing the coke.

A charge of about 5 tons of bituminous coal is dropped through the crown opening and leveled off. The door at the base is then bricked up, with the exception of a slit at the top about 1 inch wide left as an inlet for air. The mass gradually gathers heat from the masonry, which is still hot from the previous charge, until the ignition point of the slowly distilling gases is reached and they begin to burn in the open space above the coal. Sufficient air to support their combustion is admitted through the slit left in the door.

The heat of oxidation of the gases raises the temperature of the coal rapidly, and distillation proceeds quickly from top to bottom of the coal. The coal increases in volume considerably during distillation, then fuses into a pasty mass, and finally, when all volatile gases have been driven off, it again becomes solid and shrinks below its original volume. The air supply must not be in excess of that required for the oxidation of the gases, as an excess means oxidation of the carbon of the coke.

The time required for making furnace coke is about forty-eight hours, while the better grade of foundry coke requires about seventy-two hours.

When distillation is complete, the door is opened and the coke is sprayed with water. The consequent cooling causes contraction and splitting up of the solid mass into fragments whose lengths represent the depth of the bed of coke. The entire mass is now withdrawn and further cooled with water, and the oven is immediately recharged.

The "by-product" coke process differs from the beehive method in that the coking is accomplished in a closed retort, the gases being saved.

Retort or *by-product coke* is made in one of two types of retort ovens — the Semet-Solvay retort, and the Otto-Hoffman retort.

The Semet-Solvay retorts are long narrow chambers arranged in batteries of a score or more, the individual retorts being separated by heavy masonry walls. Openings are provided above for the charging of coal, and for the escape of gas. The retort walls are lined with hollow flue tiles and a part of the gas driven off from the retort charge is mixed with air and burned in these flues. The heavy brick walls between the retorts are thereby heated to a high degree and the heat retained tends to equalize the temperature in the retort at the beginning and end of the process.

A charge is coked in eighteen to twenty-six hours. The retort is charged by overhead mechanical devices, and the coke is discharged by a mechanical pusher which forces the entire retortful of coke out bodily. The water cooling is done outside the retort.

The distillation begins at the retort walls and proceeds inward. The products of distillation are conveyed by a collecting pipe to the condensing plant where they are relieved of the tar, ammonia, etc.

The Otto-Hoffman retort oven differs from the Semet-Solvay retort principally in that provision is made for using a part of the heat of the escaping products of combustion to heat the incoming gas and air which are mixed and burned in the flues surrounding the retorts. The retorts are arranged in batteries of about fifty. The intervening walls are 12 inches thick and contain the flues in which the gases are burned. For this purpose about one-half the purified gas from the retorts is used.

The operation of the furnace involves the regenerative principle. The escaping hot products of combustion in the flues are led through chambers in which brick are piled to form a loose checkerwork. In their passage they heat up the brickwork of the regenerative chamber before passing on to the stack. After a definite interval of time the course of the escaping burned gases is diverted to a second set of regenerative chambers. The air and gas which are to be used in heating the retorts are now admitted separately through flues beneath their respective hot regenerative chambers and in passing up through the hot checkerwork become heated before reaching the flues where they are burned. The direction of circulation of the gases through the flues is reversed at frequent intervals so that one set of regenerators is always being heated by the burned gases while the second set is performing its function of preheating the incoming gas and air.

A charge is coked in from twenty-four to thirty-six hours, the charging and discharging, and also the condensing of the products of distillation being accomplished in a manner similar to that used in the Semet-Solvay process.

19. Charcoal Manufacture. Charcoal was at one time commonly made by burning in heaps without recovery of the by-products. The percentage of volatile constituents of wood is much higher than is the case with coal, however, and the waste in charcoal-making is therefore much greater than in coke-making. This fact largely accounts for the early adoption of kilns and closed retorts in charcoal-making. Most of the charcoal now made is burned in by-product retorts with recovery of wood alcohol, acetic acid, tar, gas, etc.

MANUFACTURE OF PIG IRON

20. The Blast Furnace Process in General. Practically all of the iron used commercially, whether it be used as cast iron, wrought iron, or steel, is first reduced from the ores in a blast furnace to form pig iron. The process of smelting iron in the blast furnace consists essentially of charging a mixture of fuel, ore, and flux into the top of the furnace, and simultaneously blowing in a current of air at the bottom. The air burns the fuel, forming heat for the chemical reactions, and for melting the products; the gases formed by this combustion remove the oxygen from the ore, thereby reducing it to metallic form; and the flux renders the earthy materials fluid. The gaseous products of the operation pass out at the top of the furnace, while the liquid products, pig iron and slag, are tapped off at the bottom. The escaping gases are combustible, and therefore are conducted through pipes to boilers and stoves, where they perform the useful service of heating the blast and raising steam or operating internal combustion engines.

The essential equipment of a smeltery consists of the blast furnace itself, the equipment for handling the charges and the products, stoves which preheat the air used for the blast, and blowing engines which supply air under pressure and deliver it to the furnace.

21. The Blast Furnace and its Mechanical Equipment. The blast furnace (Fig. 1) consists of a vertical shaft built of steel and lined with firebrick. The lower portion, called the "hearth" or "crucible," is cylindrical, about 8 feet high, and 15 to 17 feet in diameter. It contains the "tuyères," the "cinder notch," and the "iron notch," and serves as a crucible in which the molten products of the operation are collected. Above the hearth the walls diverge, forming an inverted truncated cone called the "bosh," which is 12 to 13 feet high and 22 to 24 feet in diameter at the widest point. Above the bosh extends the "stack," converging to a diameter of about 16 to 18 feet at the "throat" at a height of 45 to 60 feet above the bosh.

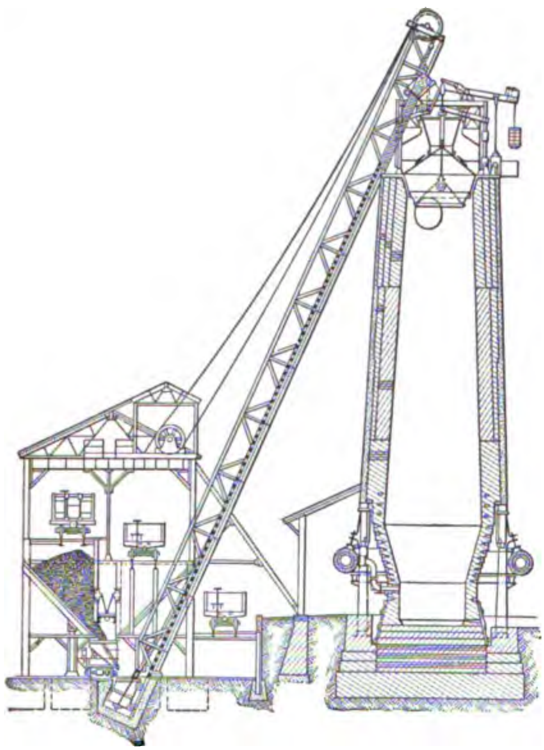


FIG. 1. — Blast Furnace and Charging Mechanism. (Campbell.)

The shell of the shaft above the bosh is so constructed as to be independent of the parts below. It is supported by a steel ring called the "mantle," resting upon columns. The walls of the shaft portion of the furnace, called the "inwalls," have a lining, usually 27 inches thick, of hard, high-silica, fireclay brick designed to resist abrasion. The lining of the bosh is also 27 inches thick, except when the bosh is surface-cooled, in which case a 9 to 13 inch lining is used. The lining of the hearth usually increases in thickness downward, being more than 30 inches thick at the bottom. A more refractory but softer fireclay brick is used in the lining of the bosh and hearth.

The ring of "tuyères" pierce the hearth lining just below the bosh. There are 8 to 16 pipes having an internal diameter of from 4 to 7 inches, through which the hot blast of air is driven. Both the tuyères and the tuyère-blocks are protected from burning by being made of hollow metal construction and cooled by water circulating through them.

The hole for tapping off the liquid slag, called the "cinder notch," is located on the side of the hearth about 3 feet below the tuyères. This also is protected by a water-cooled casting. It is closed by stopping up the hole by an iron bar having an enlarged end, until the slag itself has solidified and plugged the hole.

The "iron notch" or "tap-hole," used for tapping out the molten iron, is located at the very bottom of the hearth in the front or "breast" of the furnace. It is commonly stopped by ramming in several balls of clay.

The hottest part of the furnace, the bosh, is cooled in one of two ways: The older method involves the use of thick walls in which wedge-shaped hollow castings are inserted. These "cooling plates" are provided with inlet and outlet pipes and are kept full of circulating water. They are so placed as to form a series of rings from 1 to 2 feet apart vertically. The second method consists of "surface-cooling" of the bosh walls, which in this case are not over 13 inches thick. The cooling is accomplished either by sprays of water directed against the bosh jacket from all sides, or by a spiral trough winding about the boshes and kept full of running water.

A modification of the blast furnace consists in the application of surface cooling to the entire stack of the furnace. This necessitates the use of a thin lining of the "in-walls," usually 12 inches. Both the spiral trough and the spray method of cooling are used.

The increase in sectional area as the material sinks below the level of the stock line allows for the natural expansion at the higher temperature, and tends to prevent clogging. The reduction in the bosh holds up the material until the fuel is burnt out, and the liquid iron and slag gradually drop into the hearth, where their difference in specific gravity causes them to separate, permitting them to be tapped out separately.

The combustible gases generated during smelting are taken from the furnace just below the bell through outlets, one to four in number, which converge into a single large pipe called the "down-take." An auxiliary pipe connected with the gas outlet pipes, and provided with a valve called the "bleeder," serves as an emergency relief at times of unusual gas pressure.

Near the lower end of the down-take the "dust-catcher" is placed. This is simply an enlargement of the pipe designed to remove solid particles carried over into the down-take by reason of the velocity of the current of gases. The gas can now be used under boilers or in hot-blast stoves, but cannot be used in internal combustion engines without having first been cleansed in some type of washing device wherein all suspended matter is removed by water. In American practice two long rows of storage bins behind the blast furnaces are kept filled with ore by bottom-dump cars or a conveying device. Between and under the bins runs a track upon which "ore larries" are switched back and forth containing in succession weighed amounts of ore, flux and fuel. These cars discharge into the loading skip of the blast furnace. The charging is accomplished by means of a long double-track inclined skipway, the mechanism of which is controlled from the ground level. The skips are loaded by gravity from the larries, elevated to the top of the furnace, and discharged into the hopper automatically.

The upper hopper of the furnace is closed at the bottom by an inverted iron cone called the "bell." By lowering the bell the contents of the upper hopper are allowed to fall into the hopper proper of the furnace. This larger hopper is also closed by a bell. At intervals the bell is lowered and the contents of the hopper are distributed in an even layer upon the material already in the furnace. At this time the upper hopper is closed so that there is never a direct opening from the interior to the open air. Sometimes elaborate devices are installed to insure an even distribution of the charge as it falls into the furnace, avoiding the segregation of the fine and coarse material that is apt to be caused by the ordinary bell.

22. Hot-blast Stoves. Each furnace is connected with from three to five hot blast stoves. The design of the stove varies, but the same principles govern the operation of all.

The stove consists of a vertical steel cylinder, 20 to 22 feet in diameter and 80 to 110 feet high, containing two firebrick chambers. The central chamber is open, while the outer annular chamber is divided into a large number of small flues. Gas from the blast furnace and a definite proportion of air are admitted at the bottom of the open chamber and burned. The products of combustion rise to the top of the furnace and pass downward through the small flues and thence to the stack. The greater part of their heat is taken up by the brickwork of the flues. After burning gas in a stove for about three hours the latter is hot enough to heat the blast.

Air from the blowing engines is now admitted at the bottom of the small flues in the outer chamber and passes upward, taking up the heat stored in the brickwork. Thence it passes downward through the central flue to the furnace. The blast temperature is kept fairly uniform by working about four stoves per furnace, keeping three always "on gas" while the fourth is "on air," and changing stoves about once an hour.

23. The Blowing Engines. The air for smelting is delivered under pressure by blowing engines, which deliver the air at a pressure of from 15 to 30 pounds per square inch. The blowing engines are driven by steam or by internal combustion engines which utilize the gas from the blast furnace.

24. Drying the Blast. The presence of moisture in the air of the blast means an expenditure of a large amount of fuel which serves no purpose other than dissociating the water vapor. For this reason most furnaces are equipped with refrigerating devices whereby the air is cooled far below its dew-point, and its moisture largely reduced by condensation before being drawn into the blowing engines.

THE FUNCTIONS OF THE BLAST FURNACE

25. General. The blast furnace has five distinct duties to perform:

Deoxidize the iron ore;
Carburize the iron·
Melt the iron;
Render fusible and melt the slag;
Separate the molten iron and the slag.

26. Deoxidation of the Iron Ore. The recovery of iron would be impossible without deoxidation, because of the operation of the general principle that oxidized bodies in a state of fusion will not unite with unoxidized ones. The application of this principle to the metallurgical processes in iron- and steel-making may be stated as follows:

First, when an element such as carbon, silicon, or phosphorus, existing in chemical union with a metal, combines chemically with oxygen, the resulting oxidized product must, when melted, separate itself from the remaining metallic portion.

Second, if oxidized metal parts with its oxygen and becomes reduced to the metallic state, the newly liberated portion joins the metal in the furnace.

If, therefore, the iron were not reduced, the iron oxide would not be recovered, but would be lost with the slag.

27. Carburization of the Iron. Carburization of the iron is essential because at the temperature attained in at least the greater part of the melting zone it would be impossible to melt free iron, whereas iron saturated with carbon is sufficiently superheated beyond its melting-point to make it very fluid, so that it easily becomes separated from the slag in the hearth.

28. Melting the Iron. When fusion takes place all oxidized bodies unite to form the slag and expel therefrom all fused unoxidized bodies. It is, therefore, essential that the iron be fused in order that it may be expelled from the slag. The molten iron will necessarily absorb all deoxidized substances such as silicon, manganese and phosphorus, which exist as free metals or metalloids in the lower portion of the furnace. Carbon will also be absorbed until the saturation point is reached.

It is further essential that the iron be not only fused but superheated, in order that it may remain fluid until drained from the furnace and cast into pigs or transported to steel furnaces.

29. Conversion of Gangue to Fusible Slag. The function of the slag formed in the blast furnace is primarily the elimination of all non-volatile matter in the gangue of the ore and in the fuel which does not properly belong in pig iron. This can be accomplished only by giving to the slag such a composition that it will offer a greater attraction to the impurities than does the metal.

The slag-making materials consist of the gangue of the ore, the ash of the fuel, and the lime of the flux. The chemical nature of the slag and consequent metallurgical action is controlled by varying the relation of lime to the other slag-making constituents in the furnace charge. The slag-making materials upon fusion form a molten silicate of lime, together with magnesia and alumina. The alumina and earthy and alkaline bases naturally enter into the slag, since they exist as oxides and are not reduced in the furnace. In addition, the bulk of the silicon will enter the slag as silica (SiO_2), and most of the sulphur, by an entirely chemical action, enters the slag as sulphide of calcium, which, although an unoxidized body, does not unite with the molten iron, but appears to dissolve in the slag.

30. Separation of Iron and Slag. The two substances are chemically mutually repellant, and both are very fluid and of different specific gravities. The slag floats upon the molten iron in the hearth of the furnace and may be readily tapped off through the cinder notch above the level of the iron.

OPERATION OF THE BLAST FURNACE

31. Starting the Furnace. A new furnace must be first dried for several days by a wood fire built in the hearth. After drying, a scaffold is built just above the tuyères and two or three courses of cord-wood placed vertically are laid thereon. The wood is followed by a blank charge of coke mixed with enough lime to flux its ash, extending to a point about midway in the height of the furnace. Upon this bed of coke the charges of fuel, ore and flux are begun and the furnace completely filled. Kindling is placed beneath the scaffold, kerosene is introduced in the tuyères, the top of the furnace is opened, a light blast started, and the kindling ignited.

The top is kept open until the wood smoke disappears, after which the gases are taken care of by the down-take. Charging continues as the stock line settles, the proportion of ore and flux to fuel being gradually increased until the normal burden is reached in a week or ten days.

32. Mechanical Control of Furnace and Accessories. The computed proportions of ore, flux, and fuel are weighed in the ore larries before being discharged into the loading skips. Various devices are used for accomplishing an even distribution of the stock as it falls into the furnace, the intention being the prevention of segregation of the coarse and fine material.

The hot-blast stoves are controlled by a series of valves, which regulate the admission of gas, the admission of air from the blowing engines, the outlet of hot gases to the furnace, and the chimney draught while "on air."

The temperature of the furnace is mechanically controlled by control of the temperature and pressure of the air blast.

The slag must be tapped off within ten to fifteen hours after starting the blast and thereafter about every two hours, the intervals becoming shorter as the level of the molten iron rises toward the level of the slag notch. The iron is tapped about twenty to thirty hours after starting the blast and thereafter at intervals of about four to five hours. Peep holes are provided in the furnace walls so that the proper time for tapping slag or iron may be observed.

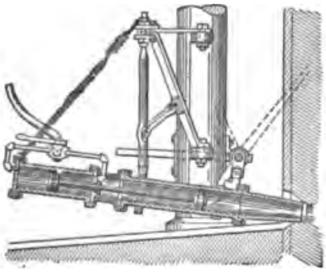


Fig. 2. — Gun for Plugging Tap Hole.

The cinder notch is opened up by use of a pointed bar, and closed by holding in the hole a bar (having an enlarged end) until the cinder chills against it. The iron notch is opened by drilling through the clay which closes it, and finally driving in a pointed bar. It is closed either by cutting off the blast and driving in balls of clay by hand tools, or by a machine called the "gun" (Fig. 2), which by action of a piston drives balls of clay into the tap-hole without requiring complete cutting off of the blast pressure.

33. Metallurgical Control of Furnace. The strength of the deoxidizing agencies may be regulated by controlling the hearth temperature, by varying the furnace burden, and by varying the slag composition.

The hotter the furnace the more powerful will be the deoxidizing action. Increasing the fuel ratio has a direct effect upon furnace temperature, and an indirect effect in increasing the deoxidizing action. Increasing the lime-magnesia content of the slag has the effect of raising its melting-point and as a result the hearth temperature is again increased with consequent increase in the strength of deoxidizing agencies.

Control of Hearth Temperature. The hearth temperature may be raised in three ways: by increasing the proportion of fuel to ore and flux; by raising the blast temperature and pressure; and by making the slag more infusible. The first and second methods need no further explanation. Making the slag more infusible raises the hearth temperature because a very fusible slag becomes very fluid high up in the melting zone and rapidly traverses the hottest part of the furnace without opportunity to absorb much heat. A less fusible slag, on the other hand, will descend slowly through the hottest part of the furnace, gradually melting and becoming superheated, so that when it finally trickles down into the hearth it will convey a great amount of heat.

Burdening the Furnace. The proportion of ore and flux to the fuel in the furnace charge is called the furnace "burden." Successful operation depends more upon the proper burdening than upon any other single factor in the furnace management. The method of determining the furnace burden is somewhat complex, and is dependent in its details upon the experience gained in the use of given ores.

The flux required is expressed in tons of stone per ton of pig iron produced and the total, when a slight addition has been made to flux the sulphur, will express the total tonnage of limestone to be charged per ton of pig iron made.

The tonnage of ore required per ton of pig iron produced may be calculated directly from the percentage of iron in the ore. The amount of fuel required per ton of iron produced is fixed by two considerations: first, the amount of carbon required to form and melt the slag, and second, the amount of carbon required to reduce, carbonize, and melt the pig iron. These requirements are separately computed, the factors employed being largely determined by the experience of the furnace manager. The quotient of the total carbon required by the percentage carbon in the fuel is the coke required per ton of pig produced.

Very commonly in American practice two distinct kinds of ore must be charged, one a soft earthy ore such as is mined on the Messabi range, the other a rock ore which must be used to prevent clogging of the furnace by the earthy ore. The problem of determining the furnace burden is not materially affected except that the two ores must be considered separately, and the proportion of each as well as the fuel and flux requirements of each is separately determined.

34. Action within the Furnace. *Solids and Gases.* In consequence of the fact that all of the solid material used in the blast furnace is introduced at the top, while the air, enters at the bottom, we may consider that we have in the furnace two moving currents; one a slow current of descending solids, the other a rapid current of ascending gases. The interactions of these two currents constitute the greater part of the changes which take place outside of the smelting zone.

The Fuel and Heat Development. The primary source of heat in the furnace is the carbon of the fuel, and if all of the carbon were completely burned the total heat developed would simply be 14,550 B.T.U. per pound of carbon. Since the furnace gases are combustible, however, it is evident that not all of the carbon is completely burned, and since pig iron contains carbon, it is further evident that a part of the carbon is not burned at all.

The carbon that is used to reduce the oxides of iron, silicon, manganese, phosphorus, etc., is all completely burned to CO_2. The balance of the carbon in the fuel, after that absorbed by the iron and a further quantity required to reduce the CO_2 of the flux to CO has been deducted, is burned to CO.

In addition to the heat developed by the burning of carbon there is a secondary source of heat, the heat in the air blast.

Chemical Reactions. The exact nature and sequence of chemical reactions in the blast furnace are not easily determined and there is considerable divergence in opinions of various authorities, but in general the chemical phenomena of a blast furnace as the charge passes through are as follows:

The ore as it enters the furnace encounters an atmosphere of gases made up of CO_2, CO, and N. The Fe_2O_3 of the ore immediately begins to be reduced by CO, forming Fe_3O_4 with the evolution CO_2 and attended by the freeing of a certain amount of carbon. (This carbon becomes deposited in the form of lamp-black upon the solid material of the charge and on the walls of the furnace.) When the material has sunk 12 to 15 feet below the stock line, the newly formed Fe_3O_4 begins to be further reduced by CO to form FeO, attended by the further evolution of CO_2. Then the FeO begins to be reduced by CO to metallic iron at a temperature of 700° C. (1292° F.), and practically none exists at temperatures above 800° C. (1472° F.). The iron at this time assumes a spongy form.

The decomposition of the limestone begins at a temperature of about 800° C. (1472° F.), and is completed very quickly. The CO_2 liberated is rapidly reduced by C to CO, while the lime descends to the zone of fusion to flux the acid portion of the charge.

The travel of the materials through the region between the point of completion of the decomposition of limestone and the upper limit of the smelting zone is characterized by no chemical action. During this transit the materials absorb much heat, however, and the temperature rises steadily as the tuyères are approached.

The portion of the furnace constituting the lower part of the bosh is called the "smelting zone." It is characterized by chemical actions impossible above this zone because of insufficiently high temperatures. The air of the blast is immediately separated at the tuyère level into oxygen and nitrogen, and the latter, being practically inert, passes upward in substantially its original volume. The oxygen immediately burns the carbon of the coke to CO_2, which is in turn rapidly reduced to CO.

The smelting zone is from a chemical point of view primarily the zone of reduction of the metalloids (manganese, silicon, and phosphorus) through the agency of solid carbon, and the removal of sulphur through the joint agency of the lime of the flux and the carbon of the fuel.

The reduction of the oxides of manganese, silicon, and phosphorus by carbon is in each case attended by the evolution of CO. Perhaps two-thirds of the manganese will under ordinary conditions be reduced and therefore be found in the iron. Silica is not so readily reduced, the extent of the reducing action being largely dependent upon the hearth temperature and the composition of the slag. Phosphoric acid is readily reduced at the temperature of the smelting zone and practically all of the phosphorus in the charge will therefore be found in the pig iron.

The behavior of sulphur in the smelting zone is not analogous to that of the metalloids above considered. Whatever the original form of the sulphur in the charge it will probably reach the smelting zone in the form of ferrous sulphide, which is soluble in iron. Sulphur readily combines with the bases of the slag, particularly lime, and is thereby removed in the slag in the form of calcic sulphide, CaS. Iron is thereby restored to the metal, and the oxygen liberated in the presence of carbon reacts to form CO again.

35. Handling the Products. *The Iron.* The iron when tapped from the furnace is handled in one of two general ways; by casting into pigs or still molten in ladles.

Formerly all the iron was cast in sand pig-beds, which consist of a series of parallel depressions molded in a bed of silica sand on the floor of the cast-house. Fig. 3 shows such a pig-bed. The individual depressions are connected to cross runners which in turn connect with the main runner leading from the tap hole. Sand casting is now seldom used.

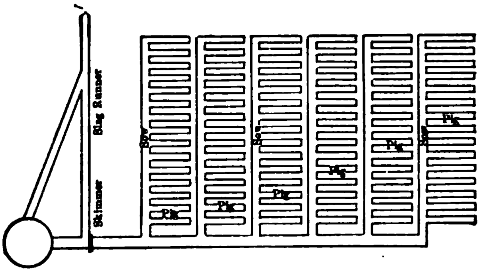


Fig. 3. — Sand Casting Pig-bed.

A modification of the sand pig-bed, the "chill pig-bed," is sometimes used. It is simply a pig-bed made of cast iron, molded in shape very similar to that of the sand pig-bed, but not requiring any preparation beyond sprinkling with a clay wash to prevent the pig iron from sticking to the molds.

The iron pigs are broken from the cross runners by hand sledges and bars or by a mechanical pig breaker, and the cross runners are similarly broken up into convenient lengths.

A large proportion of the iron molded into pigs is cast in pig-molding machines, one type of which is illustrated by Fig. 4 The machine consists essentially of a continuous series of pressed steel molds carried on an endless chain. The iron runner of the furnace delivers the molten iron into a ladle which is discharged into a spout whence the metal is poured into the molds as they slowly travel past. The iron quickly chills and is discharged into a car when the mold passes over a sheave at the end of the run. On the return the molds are immersed or sprayed with limewater to prevent the pigs adhering. The cooling of the pigs is usually facilitated by depressing the chains and running them through a tank of water.

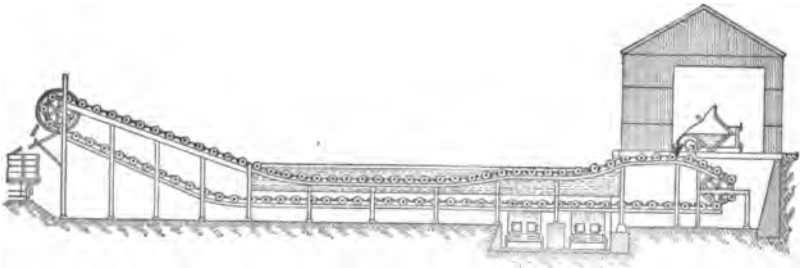


Fig. 4. — Pig-moulding Machine.

The blast furnace is so often operated in direct conjunction with a steel plant that the iron is very commonly not cast into pigs at all, but is run directly into ladles which transport it to the steel furnaces. The ladle is built of steel, mounted on trunnions on a car-truck, and lined with firebrick. Its capacity is usually 20 tons or more.

Slag Handling. The slag which accumulates above the level of the cinder notch is tapped off at intervals of about two hours, while the iron notch is closed. When the iron notch is opened iron free from slag flows at first, but later on in the cast a quantity of slag accompanies the iron, floating on top just as it does in the hearth. This slag is easily separated from the iron by a "skimmer" placed in the main iron runner. The skimmer usually consists of a permanent cast-iron trough, having a depression followed by a dam over which the iron must flow. The skimmer is suspended over the depression at such a height that it rests on top of the stream of iron and effectually prevents the slag from being carried over the dam. An opening in the side of the trough allows the slag to overflow into a runner, whereby it is carried to the main slag runner which leads from the cinder notch to the point where the slag is discharged into ladles and carried to the slag dump.

THE ELECTRIC REDUCTION OF IRON ORES

36. General Considerations. The electric furnace has been used in the metallurgical industries for a considerable period, but it is only recently that the difficulties in the way of practicable operations have been removed to such a degree that pig iron has been successfully produced on a commercial scale.

In the blast furnace fuel must be supplied to serve two purposes: the introduction of carbon, the oxidation of which supplies the necessary heat; and the introduction of carbon to act as a reducing agent. In the electric furnace the requisite heat is supplied by electrical means and the only carbon required is that needed for strictly reducing purposes. It has been shown that the electric furnace needs about one-third the amount of carbon required by the blast furnace.

On the other hand, the cost of heat produced by electrical means will usually exceed the cost of heat produced by the combustion of fuel except in ore districts where the price of fuel is very high and electric power low. It is only in such districts, therefore, that the commercial extraction of iron by electric means can be successful.

37. The Electric Furnace. Many types of electric furnaces have been used in the metallurgical industries, and may be classed as follows:

Furnaces using electrodes with an open arc, the heating being done by radiation, called "arc furnaces."

Furnaces using electrodes that project into the charge or the bath, called "resistance furnaces."

Furnaces without electrodes where the bath forms the secondary of a transformer, called "induction furnaces."

Only furnaces of the second or resistance type have been employed in the smelting of ores. Fig. 5 shows the general arrangement of a furnace at Domnarfvet, Sweden, and Fig. 6 shows a modification of the Domnarfvet furnace built at Trollhätten, Sweden. This latter furnace is similar to furnaces developed at Heroult, California, and may be described as follows: —

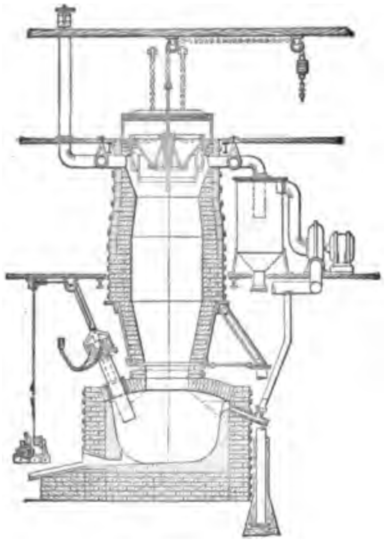


FIG. 5. — Electric Ore Smelting Furnace. Domnarfvet, Sweden.

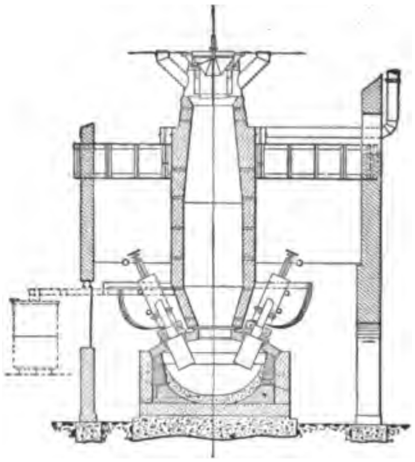


FIG. 6. — Electric Ore Smelting Furnace. Trollhätten, Sweden.

The upper portion of the furnace presents an appearance very similar to that of an ordinary blast furnace except that it is much smaller. This portion is supported on columns over a large crucible which is lined with magnesite and provided with the usual tap-holes for slag and iron. The shaft is provided with the usual charging arrangement of hopper and bell, as well as gas outlets, bleeder, down-take and dust-catcher.

The current is introduced through six electrodes which are carried by adjustable mountings so that the depth to which they project into the charge may be kept constant as they become burned away. The electrodes are built of carbon and are fitted with a screw and socket so that they can be screwed together, end to end. When an electrode has been lowered as far as it will go, a new electrode is screwed on to its top and thus no part is wasted.

The material of the charge conducts the current, and its electrical resistance develops the necessary heat for smelting. The actual reduction of the ore is accomplished as in the blast furnace through the agency of the carbon supplied by the fuel, the amount required being only about one-third that required in the blast furnace.

The pig iron produced in the electric furnace far excels in quality the usual output of the coke-fired blast furnace. This may be attributed largely to the fact that it does not contain any of the oxides which are frequently present in pig iron, owing to oxidation by the blast in passing the tuyères. The absence of nitrogen is also probably a large factor. Still another metallurgical advantage lies in the fact that the temperatures are very high and easily controlled, and the hearth lining is basic, so that a large proportion of lime may be charged, making possible a very basic slag which facilitates the removal of sulphur and even some phosphorus. These considerations have great weight when it comes to making high-grade steel from pig iron.

THE USES OF PIG IRON

38. Classification of Pig Irons. Pig irons are classified according to method of manufacture, the purpose for which they are intended, and composition.

Method of manufacture.

- Coke pig: smelted with coke and hot blast.
- Charcoal pig: smelted with charcoal, with either hot or cold blast.
- Anthracite pig: smelted with anthracite coal and coke, with hot blast.

Purpose for which intended.

- Bessemer pig: for Bessemer or acid open-hearth process.
- Basic pig: for basic open-hearth process.
- Malleable pig: for malleable cast iron.
- Foundry pig: for gray cast iron.
- Forge pig: an inferior foundry pig used for manufacture of wrought iron.

Chemical composition.

- Silicon pig: high in silicon.
- Low phosphorus pig.
- Special low phosphorus pig.
- Special cast irons (spiegeleisen, ferro-manganese, ferro-chrome, etc.).

The second of these classifications is most commonly used.

The composition of the different grades is usually specified within the following limits:

	Silicon.	Sulphur.	Phosphorus.
	Per cent.	Per cent.	Per cent.
Bessemer pig	1–2.00	not over 0.05	not over 0.10
Basic pig	under 1.00	under 0.05	not specified
Malleable pig	0.75–2.00	not over 0.05	not over 0.20
Foundry pig	1.50–3.00	not over 0.05	0.50–1.00
Forge pig	under 1.50	under 0.10	under 1.00

Any of the above irons may be called "sand-cast pig," "chill-cast pig," or "machine-cast pig" according to the method of molding.

39. The Uses of Pig Iron. Pig iron as such has no structural uses, but a considerable amount is used after remelting in the shape of cast iron. By far the greater part of all of the pig iron made is converted into steel either by the "bessemer process" or the "open-hearth process" or into wrought iron by the "puddling process." All conversion processes have for their primary object the elimination of the greater part of the non-ferrous elements present in the pig. Any of these processes will reduce the carbon content to any desired point, while the silicon and manganese are necessarily eliminated during the carbon reduction. Phosphorus and sulphur are also reduced by the puddling process and by a special form of open-hearth process called the "basic open-hearth process." The difference between various steels and wrought iron is not so much a matter of chemical composition as of physical characteristics which are dependent largely upon the conditions of conversion.

Before considering the various forms of iron a systematic classification of pig-iron products will be made. The scheme presented below is, with minor modifications, that proposed by Professor Howe.

CLASSIFICATION OF IRON

I. CARBON CLASS. (Properties chiefly dependent on carbon content.)

A. Weld Metal. (Aggregated from pasty mass without later fusion.)

1. Wrought iron. (C = 0.20% or less.)
2. Blister steel. (C = 0.20–2.20%.)

B. Cast or Ingot Metal. (Cast as distinguished from aggregated.)

1. Steel. (Malleable when cast.)

Low-carbon steel. (C = 0.20% or less)
Medium steel. (C = 0.20–0.30%)
High-carbon steel. (C = 0.30–2.20%)

1. Bessemer steel.
2. Open-hearth steel.
3. Crucible steel.
4. Electric steel.

2. Cast Iron. (Not malleable, C = 2.20% or more.)

Gray cast iron. (Carbon in graphitic state.)
White cast iron. (Carbon in combined state.)
Mottled cast iron. (Carbon partly in graphitic state.)
Semi-steel. (A mixture of cast iron and steel.)

3. Malleable Cast Iron. (Cast and then rendered malleable.)

II. ALLOY CLASS. (Properties chiefly dependent on content of elements other than carbon.)

4. *Special or Alloy Steels.*

Nickel steel.
Manganese steel.
Chrome steel.
Tungsten steel.
  (High-speed steels.)
Molybdenum steel.
Vanadium steel.
Titanium steel.
Silicon steel.

B. Ferro Alloys. (Used only to introduce certain elements into steels.)

Ferro nickel.
Ferro manganese.
Spiegeleisen.
Ferro chrome.
Ferro tungsten.
Ferro molybdenum.
Ferro vanadium.
Ferro titanium.
Ferro silicon.

CHAPTER II

WROUGHT IRON

40. Historical. The history of the development of the art of the iron maker, and the use of iron in the making of implements, machines, and structures, is almost a chronicle of the advance of civilization. Since the earliest ages iron has been the one metal of greatest value to man, and when or where the first discoveries of its virtues were made are facts which are shrouded in the mists of antiquity.

The primitive methods of derivation of iron from ores were all direct methods, and the irons produced in the charcoal fire and the Catalan forge were for the most part what is known as "wrought iron" to-day. Steel was similarly made at almost as early a period, but only under especially favorable conditions, and its production was never so common as the production of wrought iron. Primitive methods of iron refinement roughly resembling the modern crucible steel process are believed to have been used in the production of the ancient Indian and Persian steels.

Charcoal bloomeries and Catalan forges, not extensively modified or improved upon, were the only source of iron for many centuries. Furnaces which were able to render molten iron from the ores, by utilization of tall vertical shafts and stronger blast pressures were developed in Belgium during the fourteenth century, and the first method of production of wrought iron from pig iron, in what was essentially a puddling furnace, was developed in England 400 years later.

41. Definition of Wrought Iron. The term "wrought iron" is commonly applied to that commercial form of iron which is obtained by the refining of a mixture of pig iron and scrap iron at a temperature not sufficient to maintain the metal in a molten state after the removal of its impurities, the iron being intermixed with a considerable amount of the slag formed in the process.

The Committee on Uniform Nomenclature of Iron and Steel of the International Association for Testing Materials defines wrought iron as "malleable iron which is aggregated from pasty particles without subsequent fusion, and containing so little carbon that it does not harden usefully when cooled suddenly."

42. Wrought Iron as a Material of Engineering Construction. Previous to 1855 wrought iron was the most important metallic material for general structural and construction purposes. It was rolled in all manner of shapes, and was used for frames of buildings, for bridges, ships, tanks, and structures of all kinds. Tools and implements were made of wrought iron whenever a hardened edge or surface was not required. Its strength, toughness, ductility, and forgeability made it available for many purposes which could not be served by cast iron.

The introduction and rapid decrease in cost of Bessemer and open-hearth steel in the latter part of the nineteenth century gradually forced the abandonment of the use of wrought iron as a structural material. Nevertheless, wrought iron still possesses an important place among materials of construction, and bids fair to continue so indefinitely. Its principal uses are as a material for general forging operations, particularly where welding is involved, as rolled rods and bars, as wire, as welded pipe, and as a metal for roofs and sides of buildings, for tanks, etc.

THE MANUFACTURE OF WROUGHT IRON

The Wet-puddling Process

43. The Puddling Process in General. The usual process of manufacture of wrought iron consists in the melting of the pig iron in the hearth of a reverberatory furnace which is lined with iron oxides, resulting in the elimination of most of the carbon, silicon, manganese, phosphorus, and sulphur present in the charge, by oxidation. The metal becomes pasty toward the end of the process, owing to the decreased fusibility of the purer iron, and is removed as a plastic ball from which the slag must be removed as completely as possible by squeezing or hammering. The resultant "puddled bloom" is rolled into large bars called "muck bars." The bars are cut into short lengths, piled up in bundles which are wired together, heated to a white heat, and rolled down to a smaller size called "merchant bars."

This process results in the production of very pure iron mixed with from 1 to 3 per cent of slag, which the rolling process has caused to assume the form of greatly elongated particles in the direction of rolling. This circumstance accounts for the characteristic fibrous structure of wrought iron, and the purity of the metal accounts for its remarkable ductility and weldability.

44. The Iron Used. The pig iron commonly used for puddling is a grade known as "forge-pig." Its composition is from 1.00 to 1.50 per cent silicon, 0.25 to 1.25 per cent manganese, not more than 1.00 per cent phosphorus, and not more than 0.10 per cent sulphur. Comparatively high silicon is desired in order to provide sufficient slag to cover the bath of metal and prevent excessive oxidation of the iron. Manganese need not be carefully watched, because it is largely removed in the process. Phosphorus, and particularly sulphur, are not completely removed, and must therefore be kept fairly low, although their injurious effect upon the quality of the iron is by no means as marked as in the case of steel.

The weight of the charge varies according to the size and type of furnace. Ordinary single furnaces handle from 200 to 600 pounds of pig, while large furnaces, or double furnaces built in pairs without a dividing wall, may handle as much as 1500 pounds per charge. Charging is usually done by hand, the pig iron being thrown in through the firing door.

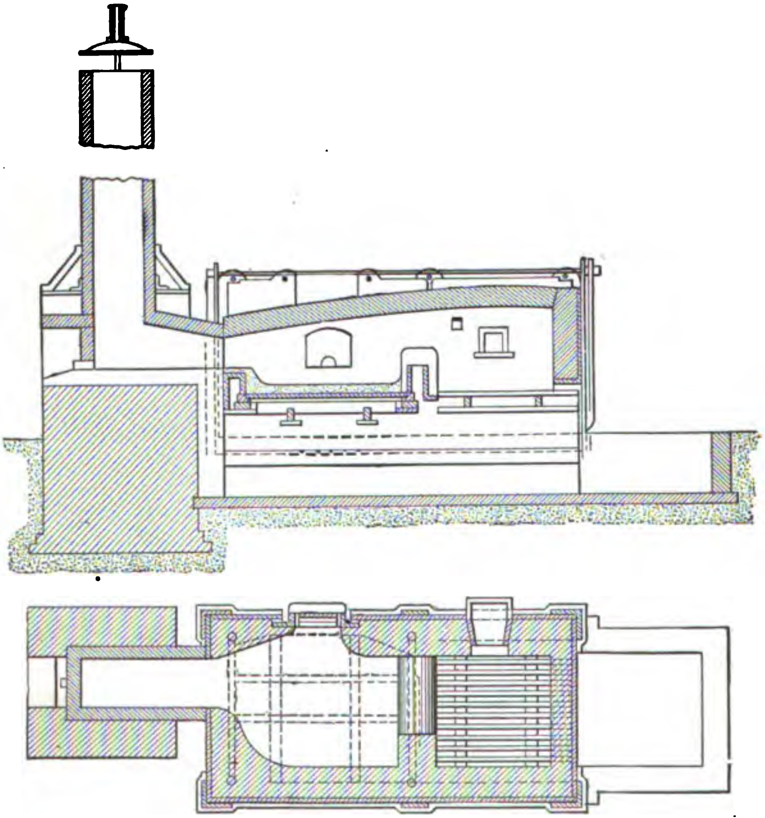


Fig. 7. — 500-lb. Puddling Furnace.

45. The Puddling Furnace. The puddling furnace is a rectangular masonry structure lined with firebrick and tied together by steel tie-rods and iron plates and buckstays. Fig. 7 illustrates a common type of puddling furnace of 500 pounds' capacity, worked from one side, and Fig. 8 illustrates a 1500-pound furnace with two workdoors. The furnace is of the reverberatory type, the heat depended upon to bring the working chamber to the desired temperature being largely that which is reflected from the sloping firebrick roof of the melting chamber, the fuel being burned in a separate chamber out of contact with the metal. Iron castings support the working bed of the furnace at a convenient height above the floor, thus permitting the free circulation of air beneath. A hollow cast-iron "fire-bridge" separates the firebox from the working chamber. It is protected from the flames sweeping across into the working chamber by a covering of refractory bricks or blocks, and is cooled by air driven through its hollow interior. The "flue-bridge" over which the waste gases pass from the working chamber to the stack is of similar construction. It is customary to arrange two or four furnaces to be worked by one stack, the flues from the individual furnaces being provided with dampers. Furnaces are not infrequently built in pairs back to back.

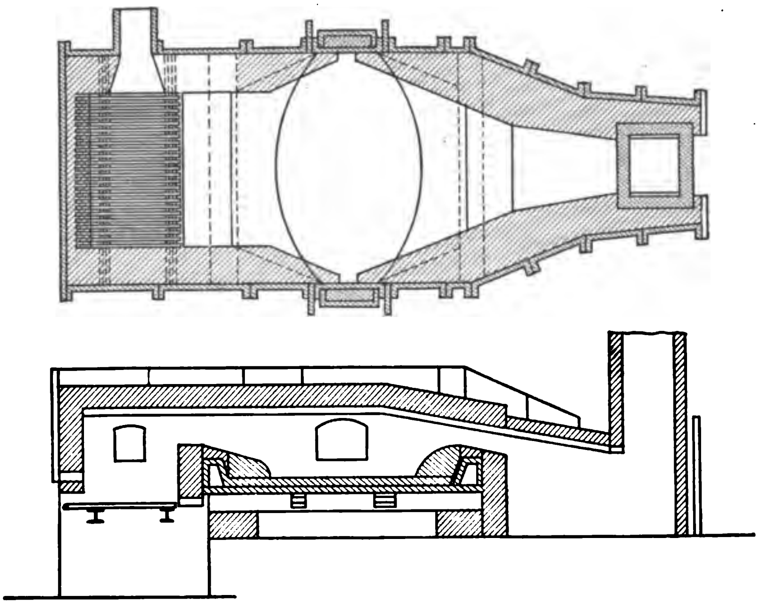


FIG. 8. — 1500-lb. Puddling Furnace.

The fuel is usually a bituminous coal which burns with a long flame. It is introduced through a "firing hole" in the front wall. The large "working door" in the front wall of the working chamber has a heavy iron projecting sill and is normally closed by an iron-bound slab of brickwork which is suspended in place and balanced by a counterweight. A small opening in the lower edge of this slab affords an opportunity for the puddler to insert his "rabbling iron" to stir or "rabble" the charge. The slag is tapped off when necessary through a tap-hole provided below the working door.

46. Preparation of Furnace for Charging. The Fettling. The furnace hearth is lined, or "fettled," with strong iron oxides of basic character. The fettling requires extensive renewals after practically every melt.

The principal "fettling" materials used are: Basic slag from reheating furnaces; slag from the puddling furnace itself, usually roasted, but sometimes allowed to remain in the furnace from the previous melt; hammer scale, or roll scale, from the finishing mill, and hematite ore.

Sufficient fettling is usually employed to cover the iron plates to a depth of about 5 inches. The character of the fettling is variable, depending upon the character of the pig iron used.

47. Furnace Operation. Chemical and Physical Changes. The furnace having been charged and a melting temperature attained, the subsequent process may be considered in four stages which merge into one another.

The "Melting-down Stage." The pig iron gradually becomes red hot and is turned about by the puddler to insure uniform heating. The more fusible slag begins to melt within twenty minutes, and in the course of half an hour the pig iron will have become completely melted down. During this stage the oxidation of the metalloids begins. The first to be oxidized is the silicon, followed by the manganese, and later by the phosphorus and a small part of the sulphur. The oxides leave the metal and join the slag. During this stage most of the silicon and manganese are thus eliminated, together with a small proportion of the phosphorus and a very small proportion of sulphur.

The "Clearing Stage." During this stage, which occupies only about ten minutes, it is usually necessary to add ore or mill scale, thus making the slag still more basic, and to close the dampers to cool the furnace sufficiently so that the carbon will not be oxidized before the phosphorus and sulphur have been disposed of. Very vigorous rabbling is necessary to promote oxidation by intimate contact between the pig iron and the fettling. During this stage the removal of silicon and manganese is almost completed, and a considerable further amount of phosphorus and sulphur is eliminated.

The "Boiling Stage." This stage is principally characterized by the removal of carbon, through the agency of the fettling first, and later by the oxygen of the air. The ferric oxide is reduced by the carbon with the formation of carbon monoxide gas which bubbles to the surface, causing the boiling appearance characteristic of this period. It is especially essential that the slag be very strongly basic at this time, as it will otherwise be unable to retain the oxides of phosphorus and sulphur which the carbon monoxide might so easily reduce.

The carbon monoxide is burned by the oxygen of the air to form carbon dioxide, resulting in the appearance of the light yellow flames at the surface of the bath called "puddler's candles." The expansion of the bath during the boil causes its level in the hearth to rise greatly and a considerable amount of slag escapes through the open slag hole.

During the boil the puddler continues to rabble the mass vigorously, and after about twenty minutes the metal begins to "come to nature," i.e., non-fluid iron begins to collect in patches in the bath and on the surface in a pasty condition, owing to its lesser fusibility in its now nearly carbonless condition. Great care is required upon the part of the puddler to prevent this pasty iron becoming chilled by sticking to the hearth, or oxidized by exposure above the slag. At the end of from twenty to thirty minutes all of the metal will have come to nature and the removal of carbon will have reached its limit. A further quantity of phosphorus and sulphur will have been eliminated during this stage.

The "Balling Stage." When all the metal has come to nature the balling stage begins. The puddler carefully gathers all of the pasty metal into one mass, which he subsequently subdivides into portions of such size as he is able to withdraw from the furnace. Each portion is worked into a ball and welded together as completely as possible. The balls are rolled up under the protection of the fire-bridge to prevent excessive oxidation of the iron before being withdrawn. The balls are finally gripped with tongs and drawn out of the door over the fore-plate and taken to the squeezers as quickly as possible. The usual weight of these "puddle balls" is between 100 and 200 pounds.

The balling stage requires about twenty minutes altogether. It is characterized by no chemical changes, but the furnace temperature must be maintained as high as possible in order that the puddle balls may be hot enough so that the slag is still very fluid when they reach the squeezer.

48. Removal of Slag. Squeezing or Shingling. The puddle ball when removed from the furnace is a very loosely agglomerated mass of pasty iron, honeycombed with pockets of slag. This slag must be removed as far as possible by mechanical means, and the iron compacted and welded together by "squeezing," or "shingling."

In American practice some form of squeezer is generally used. A very common type of squeezer is that shown in Fig. 9.

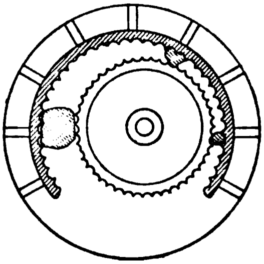


Fig. 9. — Rotary Squeezer.

A wheel mounted on a vertical axis revolves within an encircling cylinder of cycloidal form. Both wheel and cylinder have corrugated surfaces. The puddle ball is introduced at the point where the space between the two surfaces is a maximum, and the rotation of the inner wheel causes the ball to roll as it is carried around the annular space which is constantly decreasing in width. When the ball is finally ejected a large part of the slag will have been excluded and the metal will have been compacted by the kneading and squeezing.

The puddle ball may also be "shingled," i.e., forged down by some type of power hammer. The steam hammer is usually employed in shingling Between blows the puddle ball is constantly turned by the operator until it has been thoroughly welded together and the slag largely excluded.

The compression of the porous mass of metal either in squeezing or shingling results in a considerable rise in temperature of the mass, which circumstance favors the expulsion of the slag by retaining it in a very fluid condition.

49. Rolling Mill Operations. The puddled "blooms" from the squeezer or the shingling are immediately transferred to the rolling mill wherein the finished bar or shape is produced. The bloom is first passed through a bar mill which reduces it to rectangular bars called "muck bars" which are 2 to 4 inches thick. These muck bars are then cut into strips which are piled up (Fig. 10), tied with wire, reheated to a welding heat, and again rolled down to form "merchant bars." A further quantity of slag is squeezed out in rolling. Usually the bars in a pile are all laid the same way, but occasionally they are "cross-piled," i.e., alternate layers are laid crosswise. This practice results in the production of a cross-network of fibres, instead of having all the fibers running lengthwise of the bar.

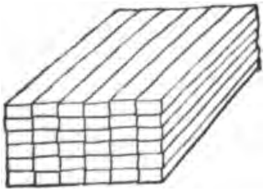


Fig. 10. — Method of Piling Muck Bars.

Bars which have been piled and rerolled are commonly called merchant bar or "single-refined iron"; when subjected to a second piling, heating, and rerolling, "double-refined bar" is produced. The effect of repeated rerolling is principally the further elongation of the strands of slag in the direction of rolling, thereby rendering the iron still more fibrous in its structure. No advantage is gained by piling and rolling more than three times.

The final rolling is usually done in a mill called a "merchant bar mill," Fig. 11. A series of passes through the rolls serves to gradually reduce the bar to the desired size and shape. Roughing rolls are shown at *B* and *D* while finishing rolls for ovals and rounds are shown at *F* and *H*.

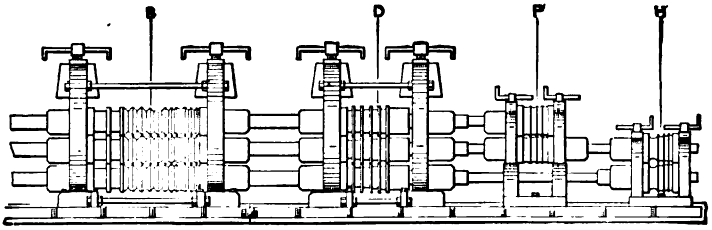


Fig. 11. — Merchant Bar Mill.

50. Mechanical Puddling. Efforts to avoid the very severe manual labor involved in hand puddling, by the use of devices which mechanically rabble the charge, have characterized the history of the industry for many years.

A well-known mechanical furnace is the Roe furnace, shown in Fig. 12.

It is suspended upon trunnions and caused to oscillate in each direction. Oil fuel is used, the oil and air for combustion being introduced through the hollow trunnions. A stack is provided at either end. The oscillations of the furnace keep the bath and slag well mixed, thus avoiding hand rabbling. The entire charge of the furnace, weighing about 4000 pounds, is discharged in one ball from which the slag is squeezed in a large hydraulic squeezer of special design.

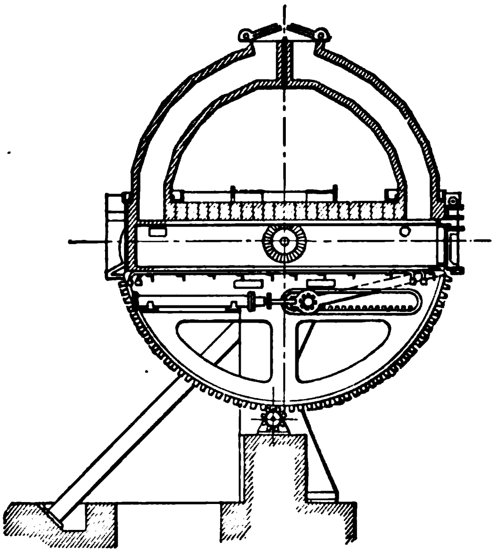


Fig. 12. — Roe Mechanical Puddling Furnace.

51. Wrought Iron from Scrap. A considerable proportion of the wrought iron made in this country is made, not by refining pig iron, but by heating and rolling scrap wrought iron.

Usually this scrap is simply bundled together and wired in a pile roughly resembling a pile of muck bars, heated to a welding heat, and rolled.

A second method of utilizing scrap is called "busheling scrap." Scrap iron of small size is gathered together, heated in a small furnace resembling a puddling furnace, and the product treated as an ordinary puddle ball.

A third method is called "fagoting," or "box piling." A rough box is made of muck bars which form the sides, bottom, and top, while the interior is filled with miscellaneous small scrap. This mass is wired together and handled just as a pile of muck bars would be handled.

All of the methods of making wrought iron from scrap without remelting result in the production of an inferior grade of material.

PROPERTIES AND USES OF WROUGHT IRON

52. Composition and Constitution. The composition of wrought iron approaches pure iron more closely than any other commercial form of iron. The usual impurities, carbon, silicon, phosphorus, sulphur, and manganese, are always present in small amounts, in addition to the slag which is invariably present. The following analyses are examples of the composition first, of an ordinary grade of wrought iron, and second, of a very pure Swedish charcoal iron:

Element.	Ordinary wrought iron, per cent.	Swedish iron, per cent.
Total carbon	0.100	0.050
Silicon	0.200	0.015
Phosphorus	0.150	0.055
Sulphur	0.030	0.007
Manganese	0.010	0.006
Slag and rare elements	2.800	0.610
Iron (by difference)	96.710	99.257

The constitution of wrought iron is quite simple as compared with that of cast iron, because of the very low percentages of carbon and other impurities in the iron. The great bulk of the material is nearly pure ferrite contaminated with small amounts of silicon, phosphorus, etc. The appearance of a longitudinal section of wrought iron under high magnification is shown in the photo-micrograph of Fig. 13. The presence of slag, appearing as many irregular black lines of varying thickness, is clearly evident. The crystalline nature of the ferrite can also be plainly seen. The micro-photograph of Fig. 14 shows the appearance of the transverse section of wrought iron. The structure is in every way similar to that revealed by the longitudinal section except that the slag here appears as irregular dark areas corresponding to the cross-section of the slag fibers.


Fig. 13. — Wrought Iron. Longitudinal Section. Magnified 100 Diameters. (Boynton.)

A third constituent besides the ferrite and the slag is invariably recognized, owing to the fact that carbon is always present in some degree. This carbon will normally combine with the iron to form cementite, which latter unites with a definite portion of the ferrite to form pearlite. Since the carbon content is normally very low, the pearlite constituent is not conspicuous, but occurs only in isolated small patches between the grains of ferrite.

The constitution of the slag itself is rather complex, being made up of silicates and phosphates of iron and manganese, formed by the combination of the acid and basic oxides which have joined the slag during the puddling process.

FIG. 14. — Wrought Iron. Transverse Section. Magnification not Stated. (Guillet.)

53. Classes of Wrought Iron. Wrought irons may be classed according to method of manufacture, or according to the uses for which they are intended.

Charcoal iron is made by refining the product of blast furnaces worked with charcoal fuel, in a charcoal hearth. *Knobbled charcoal iron* is iron made in a special type of charcoal hearth after melting in a coke refinery. Charcoal irons are the purest grades of wrought irons.

Puddled iron is that made by the wet puddling process above described. Newly puddled iron is sometimes called *muck-bar iron,* or *puddled-bloom iron,* to distinguish it from scrap puddled-iron. *Box-piled iron* may be made entirely from puddled iron or may be made from muck-bar iron and scrap.

Busheled scrap is a heterogeneous product made by heating and rolling busheled or fagoted scrap.

The principal classes of wrought iron according to the uses for which their qualitites fit them are *staybolt iron, engine-bolt iron, refined-bar iron,* and *wrought-iron plate.*

Staybolt iron is made from puddled or knobbed charcoal iron. It is the highest grade of wrought iron and, while not the strongest, it is the toughest and most ductile iron, the best for forging and welding.

Engine-bolt iron is made from the same class of material as staybolt iron, which it slightly surpasses in strength. It is slightly less tough and ductile, however.

Refined-bar iron is made from a mixture of muck-bar iron and iron scrap. It is inferior to stay-bolt and engine-bolt irons in strength, toughness, ductility and forgeability.

Wrought-iron plate is made in two grades: Class *A* is made wholly from puddled iron, and is a strong hard iron, but lacks ductility and toughness when compared with the best grades of iron. Class *B* is made from a mixture of puddled iron and scrap material, and is inferior to class *A* iron plate in every respect. Neither class of wrought-iron plate is intended for forging or welding.

54. Tensile Strength and Elongation. The tensile strength of a given wrought iron is dependent upon the direction of stress with respect to the "grain" of the iron. This is naturally to be expected, since the continuity of the metal in a direction transverse to the direction of rolling is interrupted by numerous strands of slag which are comparatively weak. The tensile strength of wrought iron in a transverse direction has usually been found to be between 0.6 and 0.9 of the strength in a longitudinal direction. It will therefore be safe to assume that this strength is about three-fourths the strength in the direction of rolling. When the muck bars have been "cross-piled" the strength in a transverse direction may nearly equal the strength in the longitudinal direction.

The tensile properties of wrought iron are quite variable; but, when the several grades listed above are recognized, the properties of a given grade become quite definitely fixed. The specifications of the American Society for Testing Materials prescribe the following tensile properties:

Property.	Staybolt iron.	Engine-bolt iron.	Refined bar iron.	Wrought-iron plate.			
				6–24 ins. wide.		24–90 ins. wide.	
				A	*B*	*A*	*B*
Tensile strength, pounds per square inch	48–52,000	50–54,000	48,000	49,000	48,000	48,000	47,000
Yield point	$0.6\binom{\text{ten.}}{\text{str.}}$	$0.6\binom{\text{ten.}}{\text{str.}}$	25,000	26,000	26,000	26,000	26,000
Per cent elongation in 8 inches	30	25	22	16	14	12	10
Per cent reduction of area	48	40					

The "Modulus of Elasticity" of wrought iron varies little for all the different grades. It will usually be found to be between 26,000,000 pounds per square inch and 28,000,000 pounds per square inch.

A typical stress-strain curve for high-grade wrought iron is shown in Fig. 15.

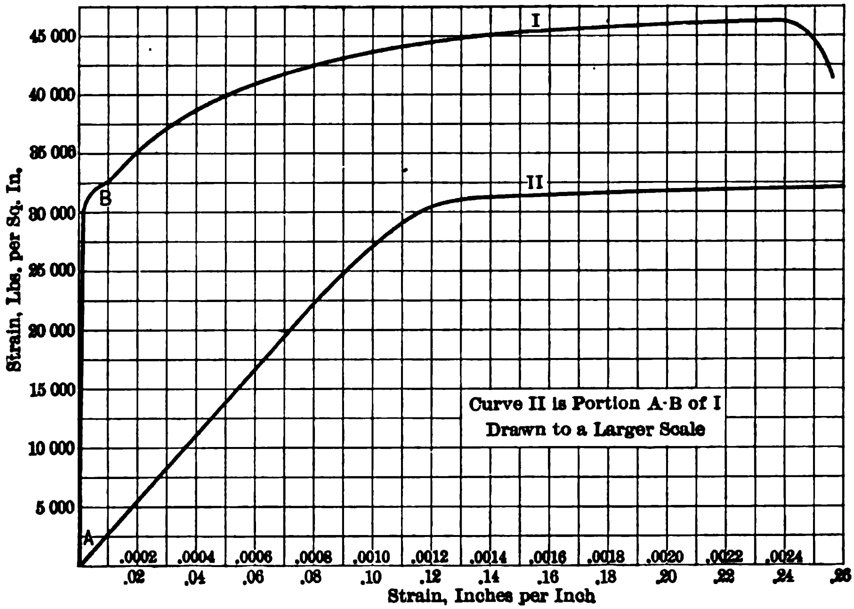


FIG. 15. — Typical Stress-strain Curve for Wrought Iron.

55. Relationship between Tensile Properties of Wrought Iron and Reduction in Rolling. A fairly definite relation exists between the tensile properties of wrought iron and the amount of reduction in rolling. It is often asserted that the strength of wrought iron is inversely proportional to the cross-sectional area. It is probable, however, that this is only true in so far as the smaller sizes represent a greater percentage reduction in rolling from the original pile of muck bars. Extensive tests made at the Watertown Arsenal show that practically the same tensile properties are shown by all sizes of wrought-iron rods provided only that the ratio of finished size of bar to size of pile be kept constant.

56. Effect of Previous Straining or Cold Working upon Tensile Properties. The effect of previous straining of wrought iron upon the elastic limit and ultimate strength revealed by subsequent test is greatly to raise the elastic limit and considerably increase the ultimate strength provided the metal has been allowed to rest after strains. The magnitude of the change effected will be dependent upon the extent to which the previous straining was carried beyond the elastic limit of the material in its original condition.

Cold working of wrought iron, i.e., deforming it by rolling, hammering, or pressing, at temperatures below about 690° C. (1274° F.), affects the structure and the mechanical properties of iron in much the same way as straining it beyond the elastic limit in a test does. The elastic limit is considerably raised, the ultimate strength is slightly raised, and the elongation or ductility is usually lowered.

The beneficial effect of cold working is largely due to the fact that it closes up the grain of the metal, and eliminates blow-holes. It also increases the cohesion and adhesion of the crystals, and if cold work follows hot work the size of the crystals will be decreased with consequent lessening of brittleness.

Of the several methods of cold working, rolling is the most rapid and the cheapest, although it does not work the metal as well as hammering. Pressing works the metal to a greater depth than either hammering or rolling and is especially necessary when the work is large. Hammering is commonly accomplished by the steam hammer, while pressing is done by hydraulic presses.

57. Heat Treatment and Crystalline Structure. The size of the crystalline grains of ferrite in wrought iron is dependent; first, upon the temperature from which it cools; second, upon the length of time it is maintained at that temperature; third, upon the rate of cooling and the amount of mechanical work to which it is subjected during cooling; and fourth, upon the temperature at which working is discontinued.

In general, the higher the temperature, the larger the crystals will be, provided the time allowed at that temperature is not too short. Slow cooling also promotes crystalline growth, provided that the cooling be undisturbed. The application of pressure, however, either by rolls, hammer, or press, retards the formation and growth of crystals and breaks up or destroys preëxisting crystals. Thorough working to a temperature below 690° C.) (1274° F.), is necessary to overcome the injurious effects of the coarse crystallization which occurs at such high temperatures as are required, for instance, in welding.

58. Compressive Strength of Wrought Iron. The properties shown by wrought iron in compression do not differ materially from its tensile properties. Its elastic limit, ultimate strength, and modulus of elasticity are about the same in compression as in tension, provided that the ratio of length to radius of gyration does not approach the point where lateral flexure occurs. In the latter event the flow of the metal when the yield point is reached immediately causes eccentricity of stress, and ultimate failure ensues under an average stress which exceeds the yield point very slightly.

The compressive strength of wrought iron is between 45,000 and 60,000 pounds per square inch if the length is short in proportion to the radius of gyration. Usually, however, this proportion is too great to make it possible to disregard flexure, and the ultimate compressive strength must be taken to be only equal to the stress at the yield point, or from 25,000 pounds per square inch to 35,000 pounds per square inch, according to the character and condition of the iron.

All of the considerations discussed above with reference to the modification of tensile properties by variations in the amount of reduction in rolling, heat treatment, previous straining, etc., apply with equal force to the compressive strength.

59. Shearing Strength of Wrought Iron. The resistance of the material to shearing stresses will be less on a plane parallel to the direction of the "grain" than on a plane which cuts the fiber of the iron transversely. The shearing strength on a transverse plane is often twice that shown on a longitudinal plane.

The actual shearing strength shown by tests is very variable, but in general will be from 20,000 to 35,000 pounds per square inch on a longitudinal plane and from 30,000 to 45,000 pounds per square inch on a transverse plane.

60. The Welding of Wrought Iron. One of the most valuable properties of wrought iron is the comparative ease with which it may be welded. Wrought iron possesses the property of weldability to a greater degree than any other metal except a very pure low-carbon steel. Its superiority is due largely to its comparative purity, since all impurities, especially carbon, silicon, and sulphur, reduce weldability in a marked degree.

The exact temperature of welding is not known, but it is moderately close to the melting-point, probably about 1350° C. (2462° F.). At this temperature the metal becomes plastic, almost pasty, and remains so for a considerable range of temperature. In welding operations, however, two factors are operative which tend to prevent a perfect union, and the production of a joint as strong as the original metal. The first of these is the formation of iron oxide by the oxygen of the air; the second is the coarse crystallization which is always apt to occur at such high temperatures.

Iron oxide forms very rapidly on iron at a welding heat, forming a coating of liquid slag which effectually prevents a proper union of the surfaces which are to be joined. The remedy lies in the removal of the iron oxide from the joint. This may be effected in large measure by simply making the two surfaces convex to each other. They then come in contact first at their centers, and as the area of contact spreads the slag is squeezed out. The exclusion of the slag is facilitated by the use of a flux which is a solvent for the slag and therefore renders it more liquid. Borax is commonly used for this purpose. Ordinary sand is a satisfactory flux in welding steel.

The effect of the rapid growth of the crystals at a welding heat is to produce a coarse-grained iron which lacks ductility and possesses great brittleness. The remedy lies in the refining of the metal by working it under the hammer or in a press until the critical range of temperatures has been passed. The danger due to coarse crystallization usually is not that the metal will be brittle just at the weld, for this portion will probably have been thoroughly refined by the working necessary to properly close the joint, but rather that the metal some few inches from the joint will have been overheated without subsequent heat refinement under the hammer. Such a joint may upon testing fail at a point somewhat removed from the weld itself, but this does not prove that the weld is stronger than the original bar.

Electric welding is an art quite distinct from ordinary hand welding. Here less difficulty is experienced in avoiding the injurious effect of oxidation, since no strongly oxidizing air blast is used, as in the case of the ordinary forge, and the pieces may be heated in direct contact with each other.

The temperature required may be attained electrically either by direct contact with — or by radiation from — an external electric arc; by making the joint itself the negative pole of an electric arc, the positive pole of which is a carbon rod; or by making the current traverse the pieces themselves, the increased resistance at the joint giving rise to the necessary welding temperature.

Owing to the possibility of great variations in the extent to which the above-mentioned factors may be operative, the strength of welded joints is extremely variable. Hand forging is usually less efficient than power forging and electric heating is more efficient than forge heating. In general the strength of hand-forged joints of average character is about 60 to 70 per cent of the strength of the bar. Power forging will raise the efficiency to from 70 to 90 per cent, and even higher efficiencies are sometimes attained by use of electric methods.

CHAPTER III

STEEL

61. Definition. It is not possible to make a strict definition of steel which is concise and at the same time not in conflict with current usage. The term is applied to practically all the forms of iron produced either in the cementation furnace, the crucible, the converter, the open-hearth furnace, the electric furnace, a combination of the converter and the open-hearth, or a combination of either the converter or the open-hearth with the electric furnace. Still there are exceptions to the above statement which cannot be disregarded, among the most important of which is the use of the open-hearth in the production of malleable cast iron.

In the early days of the iron industry it was easy to distinguish between steel and cast iron by declaring all forms of iron which were malleable to be either steel or wrought iron; steel if it would harden upon sudden cooling, otherwise wrought iron. These distinctions will not hold at the present time, however, since many grades of steel are now made which will not harden upon sudden cooling; some are not malleable except through a certain range of very high temperatures; and one grade of iron, malleable cast iron, is malleable (after annealing) but cannot be classed as steel.

Professor H. M. Howe has proposed the following definition, which, although cumbersome, covers the ground adequately: "Steel is that form of iron which is malleable at least in some one range of temperature, and in addition is either (*a*) cast into an initially malleable mass; or (*b*) is capable of hardening greatly by sudden cooling; or (*c*) is both so cast and so capable of hardening."

The provision in the definition that steel "is malleable at least in some one range of temperature" distinguishes steel from cast iron and pig iron without excluding certain special steels like chrome and manganese steel, which are malleable only through a short range of high temperatures; the provision that it is "cast into an initially malleable mass" excludes malleable cast iron, which is rendered malleable by special treatment after being cast; and either the provision that it is "cast," or the provision that it "is capable of hardening greatly by sudden cooling" serves to differentiate it from wrought iron (which is never cast and is never capable of hardening), without excluding "cementation" or "blister" steel, which is not cast but will harden, or many low- or medium-carbon steels which are cast but will not harden.

62. Classifications of Steel. Steels are classified according to method of manufacture as:

Blister or cementation steel, made by the carburization of wrought iron at a bright red heat in the cementation furnace.

Crucible steel, made by the carburization of wrought iron in a molten state in crucibles.

Bessemer steel, made in the Bessemer converter by blowing finely divided air currents through molten pig iron, thereby removing the impurities in the latter.

Open-hearth steel, made by subjecting pig iron and steel scrap to the oxidizing flame of gas and air burned in a reverberatory furnace.

Electric steel, usually made by refining steel partially purified in the converter or open-hearth in the hearth of a furnace heated by electric induction, electric resistance, or the electric arc. (Some electric furnaces produce steel from pig iron and scrap, and some produce steel direct from the ore).

Duplex steel, made by completing in the open-hearth or electric furnace the refinement of steel partially purified in the Bessemer converter.

Steels are classified according to carbon content as:

Soft, mild, or low-carbon steel, containing from 0.08 to 0.10 per cent carbon in the case of Bessemer steel, and 0.08 to 0.22 per cent carbon in the case of open-hearth steel.

Medium or medium-carbon steel, containing from 0.18 to 0.30 per cent carbon.

Hard or high-carbon steel, containing from 0.30 to about 1.5 per cent carbon.

Steels are also classified according to the uses for which their properties fit them as:

Rivet steel, boiler-plate steel, structural steel, machinery steel, rail steel, spring steel, tool steel.

THE MANUFACTURE OF STEEL

63. Steel-making Processes. Two methods of steel-making by the carburization of wrought iron have been developed. The *cementation process,* which produces *blister* or *cementation steel* by the carburization of wrought iron without fusion, and the *crucible process,* which produces *crucible steel* by the carburization of wrought iron in a fused condition.

The two principal methods of steel-making by the refining of pig iron (with or without the admixture of iron and steel scrap) are the *Bessemer process*, which produces *Bessemer steel* by blowing finely divided air currents through molten pig iron contained in a retort-shaped furnace called a "converter," the impurities being oxidized and thus removed in the slag, carbon being subsequently added; and the *open-hearth process*, which produces *open-hearth steel* by subjecting pig iron and scrap to the oxidizing flame of gas and air burned in a reverberatory regenerative furnace, carbon being restored after the removal of the oxides in the slag.

Other processes of making steel from pig iron or pig iron and scrap are usually combinations of the Bessemer process and the open-hearth or of electric furnace methods with either the Bessemer or the Open-hearth process, and are known as duplex processes

CARBURIZATION OF WROUGHT IRON

64. The Cementation Process. The principle which underlies the operation of steel-making by the cementation process is that iron at a bright red heat will absorb carbon by an action which appears to be a traveling of solid carbon into solid iron, thereby forming a solid solution of iron and iron carbide.

The bars of wrought iron which are used for the cementation process are usually very pure iron made by the charcoal-hearth process. They are usually 2½ to 3 inches wide, ½ to ¾ inch thick, and of a length corresponding to the length of the cementation pots.

The operation of the process is begun by lining the bottom of each pot with small particles of charcoal upon which alternate layers of iron bars and charcoal are placed until the pots are filled. A space is left between the bars in each layer so that each bar is completely surrounded with charcoal. The top of the pot is now luted tight with a wet mixture called "wheel-swarf," composed largely of material derived from the wear of the grindstones in the cutlery mill. This material permits the escape of gases at first, but later becomes air-tight.

The fires are now started and the required bright red heat is attained in from two to four days. The progress of the operation is tested from time to time by withdrawing and examining the fracture of trial bars which have been placed so that they project through small apertures called "moles," specially provided for the purpose in the ends of the pots.

The required temperature (about 700° C.) (1292° F.), having been attained, the carbon begins to soak into the iron at a rate of about ⅜ inch per 24 hours. The time required for the completion of the process depends upon the grade of steel produced. Mild heats require the maintaining of the maximum temperature for a period of from 7 to 8 days, medium heats require about 9½ days, and high-carbon heats require about 11 days. Since the carburization proceeds from the exterior of the bars inward, the carbon content decreases progressively toward the center, and an unaltered core will be found in very mild bars.

When the carburization has proceeded to the desired point the fire is withdrawn, and the furnace is allowed to cool for about a week before the bars are removed.

The presence of some slag in the original wrought-iron bars is responsible for the appearance of blisters on the surface of the bars, which have been formed by the evolution of carbon-monoxide gas when the carbon combined with the ferrous oxide of the slag. The presence of these blisters accounts for the use of the term "blister-steel," which is often applied to steel made by the cementation process.

The Crucible Process

65. General. Although the steel produced in very ancient times was probably made by methods similar to the crucible process, the actual invention of the modern crucible process was not made till 1740, when the efforts of Benjamin Huntsman of Sheffield, England, to devise a steel process superior to the cementation process, were finally crowned with success. For over one hundred years thereafter the crucible process remained the principal and almost the only method of steel-making, the cementation process being relegated to the position of an intermediate stage in the production of the finest cutlery steel, its product being remelted in crucibles.

The crucible process consists essentially in the melting of wrought iron in closed crucibles of refractory material, the carburizer being placed in the crucible with the iron, together with any special alloying element desired. The details of the process vary according to the type of furnace and fuel used: for the most part the gas-fired regenerative furnace is used, but in England the earlier type of coke-fired furnace is employed to a considerable extent.

66. The Coke-furnace or Melting-hole. In the steel-melting house the melting-holes are ranged along the sides of the building below the floor level. Each hole is built of masonry to hold two crucibles. The crucibles are set directly in the fuel on short stands of refractory material which are supported by the grates. The top of each chamber is covered by a slab of firebrick set in an iron frame.

The melting temperature is maintained by controlling the chimney draught, a chimney opening being provided for the purpose below the grates. The fuel used is a hard-burned coke which completely surrounds both crucibles. The fuel must be replenished several times during the operation of melting.

The clay crucibles used in the melting-hole are shown in Fig. 16. After drying, the crucibles are burned and carefully annealed, and are then heated up in the melting-hole before being charged. The maximum life of a clay crucible does not exceed 3 heats, after which the danger of breakage is very great.

67. The Gas-fired Regenerative Furnace. The gas-fired regenerative crucible-steel furnace is simply an adaptation of the Siemens type of furnace which is used in open-hearth steel making. The gas-fired furnace contains anywhere from two to twenty melting-holes, each large enough to hold either four or six crucibles. The crucibles used in this furnace are made of a mixture of clay and graphite, and are considerably larger than the all clay crucible.

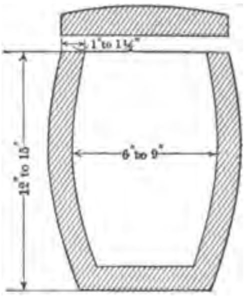


FIG 16. — Clay Crucible.

68. The Charge of the Crucible. The crucible charge is usually about 50 pounds for a new clay crucible, but must be reduced for subsequent charges, in order that the slag-line, where the wall of the crucible is attacked and weakened, may be lowered each time. The usual charge of the graphite crucible is from 85 to 100 pounds.

The crucibles are usually charged outside the furnace. The larger pieces of iron are first inserted, next the charcoal and ferro-manganese or oxide of manganese, and lastly the smaller pieces of iron.

The iron of the crucible charge should be pure puddled iron, but wrought-iron scrap and even soft-steel scrap is often substituted for a considerable part of the charge. Blister steel made by the cementation process is very frequently used in place of wrought iron in English practice, but rarely in American practice. The resultant product is claimed by the Sheffield steel-makers to be so superior to any steel made that the extremely high cost is justified.

The carburizing agent used is almost invariably charcoal, which is added in small lumps. Ferro-manganese or oxide of manganese is added to aid in forming a liquid slag and to add a little manganese to the metal.

Special elements such as chromium, tungsten, manganese, vanadium, etc., are sometimes added when special steels of the class called "alloy steels" are to be produced.

69. Operation of Process. The crucibles having been charged, the covers are put on and the temperature is gradually brought to a melting heat by building up the coke fire to the top of the crucibles in the case of the coke-furnace, or by turning on the air and gas in the case of the gas-furnace. The process is thereafter divided into two stages called "melting" and "killing."

The melting requires from two to four hours, depending largely upon the composition of the charge. Low-carbon heats take much longer than high-carbon, since low-carbon stock melts at a much higher temperature than high-carbon.

There is no sharp line of demarkation between the melting and the killing stage, as this is interpreted by the judgment of the melter, who removes the cover and examines the charge to make sure that it is entirely molten.

Killing or "dead melting" consists in holding the steel at a melting temperature until it does not evolve gases, and will pour "dead," and produce sound ingots. The change which occurs during killing consists either in boiling the gases out of solution in the metal, or in acquiring soundness by combination of the gases with silicon, which is reduced from the walls of the crucible by carbon.

When the operation of killing is complete the crucibles are gripped by a suitable pair of tongs and lifted out of the melting-hole. The cover is now removed and the slag floating on top of the steel is skimmed off by means of an iron rod with a ball of slag on one end, against which it chills. The steel is now poured or "teemed" into an ingot mold, any remaining slag being kept back by holding a bar against it. The mold used is of cast iron and has commonly a cross-section of 3 to 4 inches square; it is split lengthwise and is held together by rings keyed on. The surface of the mold is coated with smoke from a gas flame, or from burning coal-tar or resin, in order to prevent sticking and to improve the surface of the ingot.

70. Grades of Crucible Steel. Very wide ranges in composition and properties of crucible steels are obtainable. The composition is sometimes uncertain owing to the variable amount of carbon and silicon that may be absorbed from the crucible walls. Ingots are therefore always graded by breaking off the worthless upper portion containing the "pipe" and examining the fracture. Chemical analysis is usually employed to supplement examination of the fracture, and the ingots are separated into several grades of similar analysis.

No sharp subdivision of grades and uses of crucible steel can be made, but the following table shows in a general way the character of steel required for different classes of tools:

APPROXIMATE GRADING OF CRUCIBLE STEELS

(CARBON STEELS ONLY)

Uses.	Carbon, per cent.	Manganese, per cent.	Silicon, per cent.	Sulphur, per cent.	Phosphorus, per cent.
Battering tools...... Hot-work tools...... Dull-edge tools, etc..	0.45-0.65	0.20-0.50	0.20-0.30	0.02 -0.060	0.015-0.050
Dies, axes, large drills, reamers, etc.	0.65-0.85	0.20-0.40	0.20-0.30	0.015-0.030	0.012-0.025
Chisels, knives...... Drills, lathe tools...	0.85-1.10	0.15-0.30	0.15-0.25	0.010-0.020	0.010-0.020
Razors, fine lathe tools and drills.... Gravers tools, etc....	1.10-1.50	0.10-0.25	0.12-0.25	0.005-0.015	0.005-0.015

THE BESSEMER PROCESS

71. Historical. The Bessemer process for the manufacture of steel was invented by Sir Henry Bessemer in England in 1855. It is doubtful if any single invention or discovery has ever had such a wonderful effect upon industry and manufacturing in general.

For years the Bessemer process led even the open-hearth process, but the perfection of the basic open-hearth process has gradually resulted in the production of steel whose superior quality has enabled it slowly to replace Bessemer steel in one field after another.

72. The Bessemer Process in General. The Bessemer process consists in the removal of most of the impurities in pig iron by oxidation, through the agency of finely divided air currents blown through a bath of molten iron contained in a vessel called a "converter." The addition of a "recarburizer" after "blowing" is generally necessary to give the "blown metal" the required carbon content for steel.

The following operations constitute the essential features of the American Bessemer steel process:

Molten pig iron is brought from the blast furnace plant in hot-metal ladles and discharged into a large reservoir called the "mixer."

The mixer supplies molten iron as required to charging ladles, which in turn discharge into the converters, the latter being rotated into a horizontal position during charging.

The air blast of the converter is started and the vessel is elevated into a vertical position. The finely divided air currents pass up through the molten metal for a period of about ten minutes, by which time the impurities will have been practically eliminated by oxidation.

The converter is again turned into a horizontal position and the wind is cut off. A predetermined amount of recarburizer is now added in order to obtain a steel of any desired carbon content.

The molten steel is poured from the converter into a ladle which is swung by a crane over a series of cast-iron ingot molds into which the metal is teemed.

When the ingots have cooled sufficiently, the molds are stripped off and the ingots are placed in "soaking-pits" or reheating furnaces, where they remain until their still molten interiors have solidified and the temperature of the metal has become equalized throughout.

The hot ingots are transferred to the rolling mills where by a series of rolls they are reduced first to "blooms" and then to any desired shape for use in construction. Presses sometimes replace rolls.

73. The Pig Iron Used. The Bessemer process universally used in American practice is an acid process, i.e., the slag formed is of an acid character. In consequence, it is impossible to remove either phosphorus or sulphur from the iron, and a grade of pig iron specially low in these elements is required. The usual limits of composition of "Bessemer pig iron" are: —

Silicon. Per cent.	Manganese. Per cent.	Carbon. Per cent.	Phosphorus. Per cent.	Sulphur. Per cent.
1.0–2.0	0.4–0.8	3.5–4.0	0.07–0.10	0.02–0.07

At least 1.0 per cent of silicon is required in order to insure the production of a sufficient quantity of slag of satisfactory character, and also to provide heat. The oxidation of the silicon is the principal source of heat in the converter, the amount so derived being much greater than that derived from the oxidation of the carbon and the manganese.

74. The Bessemer Converter and other Equipment of the Bessemer Plant. The Bessemer converter consists of a heavy steel shell of cylindrical form supported upon two trunnions upon which it can be rotated.

The upper portion of the shell is conical and may either be concentric (Fig. 17), or eccentric (Fig. 18). The former form is more common. The clear opening at the converter mouth is usually from 2 feet to 2½ feet in diameter, the inside diameter of the cylindrical portion is about 8 feet, and the height from inside of bottom to "mouth" is about 15 feet. These dimensions apply to the average-sized converter, having a capacity of 15 tons. Converters are used, however, having capacities all the way from 1 ton to 20 tons.

The lining of the converter is usually from 12 to 13 inches thick, and is made of very refractory material of strongly acid character, silica being the principal constituent. In American practice, ganister blocks or bricks laid with thin fireclay joints are usually employed. The lining is repaired between heats with a mixture of siliceous material and clay, and more extensive repairs are made during shut-downs. Under average conditions a lining may be made to last for several months — perhaps 10,000 to 12,000 heats — before it need be entirely replaced. A new lining must be dried, and a cold lining must be heated to a red heat before the converter is charged.

The bottom of the converter is pierced with a great number of small holes, through which the air blast enters from the "wind-box" at the bottom of the vessel. The wind-box is connected by a pipe and slip ring with a hollow trunnion which communicates with the blower.

The lining of the bottom is made up of damp siliceous material bound together with clay in which the molded tuyère brick are set. The number of tuyères varies from 15 to 30 and each contains from 10 to 18 holes of $\frac{3}{8}$ to $\frac{5}{8}$ inch diameter. The total thickness of the bottom lining is from 24 to 30 inches.

On account of the fact that uncombined iron oxide has a strongly corrosive action on the lining, the bottom is corroded very rapidly, especially in the vicinity of the tuyères, where the air encounters the molten iron. This limits the life of the bottom lining to about 20 or 25 heats, even though repairs are made between heats.

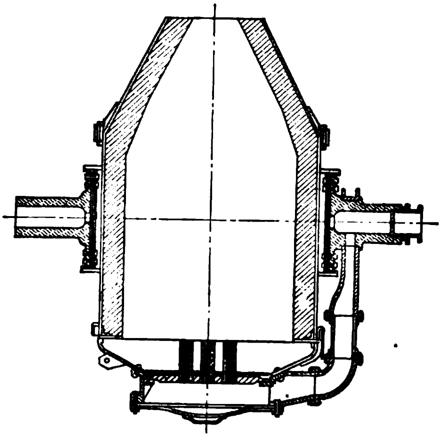


Fig. 17. — 12–15 Ton Bessemer Converter. Concentric Type.

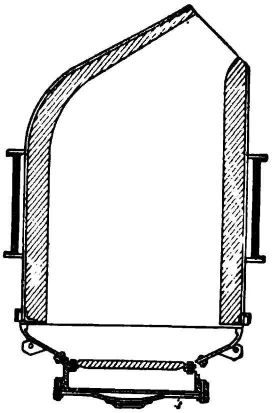


Fig. 18. — 12–15 Ton Bessemer Converter. Eccentric Type.

On this account the bottom of the converter is made easily detachable, the fastenings to the body being links secured by keys which can be quickly removed. The worn-out bottom is lowered by an hydraulic jack, located beneath the converter, on to a car which conveys it to the repair room. Meanwhile a new bottom on a second car is lifted into place and keyed on. The new bottom is carefully dried and heated to a high temperature before being put in place, and the joint with the body lining is daubed with mud before the bottom is forced into place by the hydraulic ram.

The blast is derived from blowing engines operating on steam or blast-furnace gas. A pressure of from 20 to 30 pounds per square inch is maintained. The turning on and off of the blast, as well as the movement of the converter, is all under the control of the "blower" who stands on a raised platform called the "pulpit" within full view of the entire operation.

If the Bessemer plant is not operated in conjunction with a blast furnace the pig iron is melted in cupolas which differ in no respect from the ordinary foundry cupola except in size.

More commonly, the pig iron is run into ladles at the blast furnace, and transferred to the steel plant, where the ladles are lifted by a traveling crane and discharged into the mixer, which serves as a source of supply for the converters.

The mixer (Fig. 19) is simply a large steel reservoir lined with refractory brick and mounted on rollers. Hydraulic cylinders located at the corners serve to tip the mixer to pour out the metal. The capacity of the mixer is from 150 to 500 tons. Because of its large size the mixer will hold the product of several furnaces, and tends to average the irregularities in the different irons. The mixer also serves to keep the pig iron molten for an indefinite length of time, compensates for delays either at the blast furnace or at the steel plant, and affords an opportunity for the addition of special pig iron, if necessary to correct the composition.

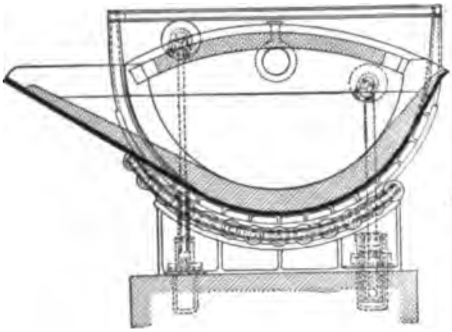


FIG. 19. — Metal Mixer.

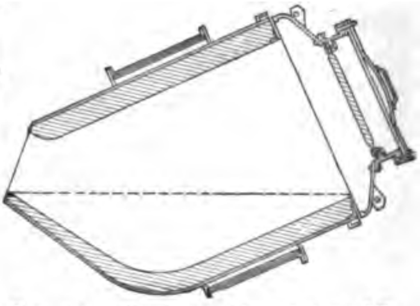


FIG. 20. — Position of Converter while Receiving Charge.

When a converter is to be charged, a ladle on a car is run under the pouring spout of the mixer and metal is poured into the ladle until the latter contains the amount required for a converter charge, as indicated by the track scales upon which the ladle car rests. The ladle car is now transferred to a point opposite the converter, the latter is rotated to a nearly horizontal position, and the charge is poured in.

75. Operation of Process. The position of the converter while receiving its charge is shown by Fig. 20. The concentric converter may be charged from either side, but the eccentric converter is always inclined in the same direction. The bath of metal never reaches the height of the tuyères before the vessel is righted. The blast is turned on after charging and before righting in order to prevent the metal from entering the tuyères. The bath of metal occupies only a small portion of the volume of the converter on account of the great increase in the volume of the bath caused by the violent ebullition of the metal during the blow.

After two or three minutes a reddish-yellow flame begins to pour from the mouth of the converter, indicating the beginning of the oxidation of carbon. This flame becomes rapidly augmented until a white-hot flame, 20 to 30 feet in height, pours out with a loud roaring sound, and a shower of sparks appears, owing to the ejection of slag and metal. Soon the flame begins to flicker and shorten, indicating that the carbon is practically burned out, whereupon the converter is immediately turned down and the blast shut off.

76. Chemistry of Process. Under the extremely active oxidizing influence of air driven through the bath of molten metal, all of the elements are oxidized, almost without regard to their relative affinities for oxygen.

Thereupon the slag formed by oxidized iron and other elements possessing a lesser affinity for oxygen, attacks the more easily oxidized elements and the latter become eliminated first.

As soon as the blow is on the silicon and the manganese begin to be burned to SiO_2 and MnO, the action being partly direct oxidation by the oxygen of the blast, and partly indirect through the agency of the FeO, and the CO which are easily robbed of their oxygen. Some iron oxide always survives, however, and with the silica forms a silicate of iron, $FeSiO_3$, which is in large part retained in the slag. Additional iron oxide is dissolved in the slag formed by ferrous silicate and manganese silicate, but a portion of this dissolved iron oxide is later reduced by carbon and manganese contained in the recarburizer.

The silicon and the manganese have been reduced to mere traces before the loss of carbon becomes appreciable. The carbon begins to become oxidized after about 2½ to 3 minutes, this being the only chemical action taking place after the silicon is eliminated until the blow is stopped and the recarburizer added. The addition of the recarburizer results in the increase of manganese and carbon, and of silicon to a lesser degree.

The phosphorus and the sulphur will not have been affected by the process, but the percentage present in the blown metal will be slightly higher than in the pig iron because of the loss of other elements which have been carried away in the slag.

The total time required for the blow is, in American practice, from nine to ten minutes.

77. Heat Development and Utilization. Silicon is the greatest source of heat in the acid Bessemer process and if the silicon in the iron is too low the result will be a cold blow. Manganese is about one-fourth as effective, while the oxidation of iron produces only about one-sixth the heat derived from the oxidation of an equal amount of silicon. Carbon, because of the fact that it is only burned to carbon-monoxide in the converter, contributes practically nothing to the net heat gained by the bath. A slight additional amount of heat is derived from the combination of oxides of iron and manganese with silica to form the slag.

78. Recarburizers and Recarburizing. The principal recarburizers used are "spiegeleisen" and ferro-manganese. Speigeleisen is a special pig iron especially high in manganese and carbon. The manganese content varies from 12 to 20 per cent and the carbon from 4 to 6 per cent. Iron alloys containing 20 per cent or more of manganese are classed as "ferro-manganese," but practically all of that which is used as a recarburizer contains about 80 per cent manganese and 6.5 to 7 per cent carbon. Spiegeleisen is always added in a molten state because it is necessary to use large amounts, and the bath would otherwise be cooled too much before pouring. For this reason small auxiliary spiegel-melting cupolas are a necessary feature of Bessemer plants.

Ferro-manganese is used to produce very soft steel, such as that used for welded pipes, soft wire, etc. It need not be molten, but is usually heated to redness before being used. The amount required for a 15-ton charge will be only about 500 pounds, or about 1.7 per cent. The steel produced is low in carbon and very low in silicon.

The recarburizer was formerly not added until the blown metal had been poured out into the ladle. At present, however, the practice is to add the spiegel to the bath just before pouring, the converter being held in a horizontal position at the time. Ferro-manganese is still sometimes added in the ladle.

79. Deoxidation. The addition of the desired amount of carbon to the blown metal is by no means the only important function served by the spiegeleisen or ferro-manganese. Blown metal invariably contains considerable amounts of oxides of carbon and iron. The CO gas is somewhat soluble in the molten metal and, even though a great part of it is removed when the spiegel is added, it continues to be evolved until the metal becomes solidified. The imprisoned CO means the presence of blow-holes in the ingots of steel.

Iron oxide is reduced principally by the manganese of the recarburizer. It is also reduced by the carbon and the silicon of the spiegel. The silicon is also very effective in reducing the carbon-monoxide gas, thereby becoming an important factor in the prevention of blow-holes.

Sometimes especially strong deoxidizing agents are used in addition to the recarburizer to eliminate the last traces of oxides in the steel. An important instance of such a practice is the addition of titanium to steel for railroad rails.

80. Casting the Ingots. When the reaction between the blown metal and the recarburizer is complete, the steel is poured from the converter into a "teeming ladle" which is suspended from a crane. The teeming ladle, Fig. 21, consists of a bucket-shaped steel shell, lined with refractory material and provided with a valve in the bottom through which the molten metal is teemed. The lining is of cheap material because the nozzle is burned out in from four to six heats. The ladle is suspended by a bale and mounted in such a manner that it may be tipped over to pour out the slag which remains in the vessel after the steel has been teemed off. The ingots are cast in cast-iron molds which are mounted on cars which are moved along a track through the mill.

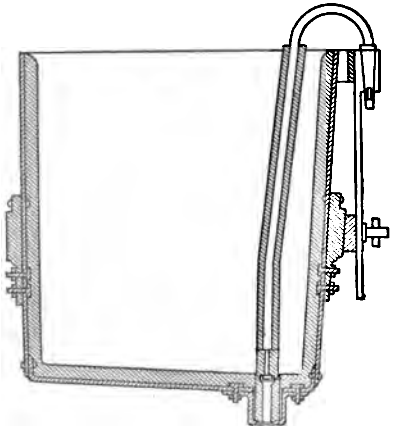


FIG. 21. — Steel Teeming Ladle.

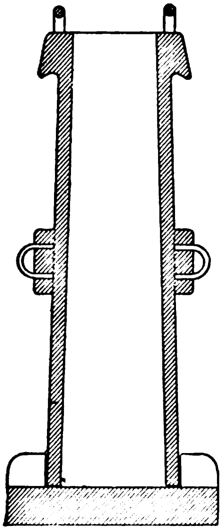


FIG. 22. — Ingot Mold.

The usual type of Bessemer ingot mold is shown in Fig. 22. The ingot produced is about 7 feet high, has an average cross-section of about 18 by 18 inches, and is about 3 inches thicker at the base than at the top in order to facilitate the stripping off of the mold.

The mold cars are moved along in such a manner as to bring each mold in succession under the nozzle of the ladle. The plunger is raised, allowing a thin stream of metal to flow into the mold, then dropped while a new mold is brought into place. The slag floats on top of the steel, and the valve is closed when slag begins to flow and the ladle is swung over a slag car and dumped.

The mold cars are drawn outside the steel mill, where the molds are stripped off by a crane, which engages the lugs provided on the molds and lifts them off, leaving the ingots standing on the iron stools which form the bottom to the mold. The ingots are then taken to the "soaking pits," while the molds are washed with clay water, allowed to cool somewhat, and run back into the mill for another cast. If the molds are not still hot from a previous heat, they must be heated before being used. The average life of molds is about 100 heats, after which they become badly cracked.

THE BASIC BESSEMER PROCESS

81. General. The basic Bessemer process differs from the acid Bessemer process only because of the different class of iron used. Basic Bessemer iron is fairly high in phosphorus, and perhaps also high in sulphur, and, since the removal of these elements is possible only in the presence of a basic slag, the addition of a certain amount of lime to the charge is necessary in order to more than neutralize the acid constituents in the iron. The fact that the slag is thus rendered basic in character makes it necessary to provide a basic lining for the converter in order that the lining may not be attacked and quickly destroyed by the slag.

The basic Bessemer process has not been used to any extent in America, owing to the availability of high-grade ore suitable for the cheaper acid Bessemer process. In Germany and in England, the conditions as to ore supply are just the reverse, and in consequence the basic process is the principal Bessemer process in use abroad.

82. The Basic Converter. The basic converter differs in no respect from the acid converter except in the character of the lining, and the further fact that the converter must be considerably larger than the acid converter of the same capacity, on account of the increased amount of slag formed.

The lining is sometimes made up of basic bricks laid in a mortar of similar character, but more commonly it is made up of a mixture of calcined dolomite with about 10 per cent of anhydrous tar used as a binder, the material being molded in place while hot by the use of a pattern. The tuyère holes in the bottom are commonly simply cored out by packing the bottom lining around wooden pins which are subsequently withdrawn.

The basic lining is much less durable than an acid lining, the average life of a lining being commonly from 100 to 200 heats, while the bottoms are good for from 20 to 40 heats.

83. The Pig Iron Used. Basic Bessemer pig iron is high in phosphorus, manganese, and usually sulphur, and relatively low in carbon and silicon. The usual limits of composition are:

Phosphorus. Per cent.	Sulphur. Per cent.	Manganese. Per cent.	Carbon. Per cent.	Silicon. Per cent.
1.0–3.0	0.02–0.30	0.3–2.0	2.75–3.5	0.2–1.0

If the phosphorus is not high the charge is apt to blow cold after the elimination of carbon. High manganese is desired to aid the silicon in producing heat at the beginning of the blow, and to facilitate the removal of sulphur which is apt to be high because of the low silicon content. The relatively low carbon content is an inevitable consequence of the presence of high manganese and phosphorus and low silicon. Only sufficient silicon to prevent too high sulphur is desirable since, with the high phosphorus content, there would be danger of producing an acid slag if the silicon were not kept low. In any event the amount of lime required to flux the acid-making constituents, phosphorus and silicon, will be increased by increasing the content of these elements.

84. Operation of Basic Process. Chemistry of Process. The basic process is divided into two more or less distinct stages. The first, called the "fore-blow," is characterized by the oxidation of silicon, manganese, and carbon, and corresponds to the ordinary blow of the acid Bessemer process. The phosphorus and most of the sulphur are removed and absorbed by the slag during a later period called the "after-blow."

Silicon, being low originally, is usually eliminated within two minutes or less, but manganese is removed very slowly because a large quantity is present and the slag is not of such a character as to take it up readily. Often some manganese is left in the iron at the end of the blow and is available for deoxidation.

Carbon is oxidized after the elimination of silicon, the removal being accomplished in slightly less time than in the acid process because of the lesser amount present.

Phosphorus is not materially reduced in amount until the carbon is practically eliminated, when it becomes oxidized and is absorbed by the slag as a phosphate of lime. A certain amount of the sulphur is also absorbed by the slag as CaS at this time. The manganese facilitates the removal of sulphur, probably by the formation of sulphide of manganese.

The quantity of lime required to make the slag sufficiently basic will vary as the composition of the iron varies. In general, however, the amount required will be from 12 to 20 per cent by weight of the charge. The lime is always charged before beginning the blow.

The time required for the conversion process with the basic converter is nearly double the time required for the acid process. The fore-blow requires from nine to twelve minutes, and the after-blow from five to six minutes. There is no indication, so far as the flame is concerned, of the completion of the after-blow, and the duration of this period is governed entirely by experience with the different irons used.

The silicon is principally depended upon to supply heat at the beginning of the process, and manganese is also an important source of heat in the early part of the blow. The oxidation of iron also supplies a certain amount of heat, but the phosphorus is the principal source, the heat developed from its oxidation being four or five times as much as that from any other source. The heat of oxidation of the carbon is largely lost by escaping from the converter mouth, as in the case of the acid process. The total heat developed in the basic Bessemer process is at least twice that developed in the acid process. But there is no greater net gain in temperature than in the acid process, because of the heat utilized in melting the flux and the increased loss to the vessel and the air because of the longer time required for the blow.

85. Recarburization. The manner of using a recarburizer in the basic process differs from that used in the acid process, because if the spiegel is added to a bath containing a great quantity of basic slag, the carbon, silicon, and manganese of the recarburizer will reduce phosphorus from the slag and restore it to the metal.

As much as possible of the basic slag is therefore poured out of the converter first, and later, as the metal is poured into the teeming ladle, a further quantity of the slag is held back and retained in the vessel. The recarburizer is then added in the ladle, and its action is thereafter similar to that noted in the case of the acid process. The deoxidizing effect if the recarburizer is no less important in the basic than in the acid process, for the oxidation of iron in the basic converter is apt to be excessive.

86. Comparison of Acid and Basic Bessemer Processes. The acid process requires the use of a higher grade of ore and one which is almost unobtainable in some countries, particularly Germany. The basic process, upon the other hand, requires a cheap ore to be commercially successful, because the process itself is expensive.

The basic process requires a high degree of skill, because of the danger of excessive oxidation and also the restoration of phosphorus to the bath through the action of manganese in the recarburizer.

THE OPEN-HEARTH PROCESS

87. Historical. The modern process of steel-making by the open-hearth method has been developed from the early work of two Englishmen, the Siemens brothers, who invented and patented the regenerative furnace in 1861. Sir William Siemens developed and perfected the early forms of regenerative furnace, making possible the utilization of this principle, in the attainment of the very high temperatures required for the making of steel in the open-hearth.

The open-hearth process developed more slowly than the Bessemer process, but now ranks first among the various methods of steel manufacture, both in metallurgical perfection and in tonnage produced.

Open-hearth steel is now exclusively used for all except the cheapest grades of steel and the time when the Bessemer converter shall be relegated to the place of simply an adjunct of the open-hearth in some form of "duplex process" appears to be not far distant.

88. The Open-hearth Process in General. The open-hearth process is so called because it consists in the oxidation and removal of impurities contained in a bath of metallic iron lying on the hearth of a reverberatory regenerative furnace, the bath being exposed to the action of the flame which sweeps across above the hearth.

As in the case of the Bessemer process, there are two modifications of the open-hearth process, depending upon the character of the charge and the slag produced. The acid open-hearth process is so conducted as to produce an acid slag, accomplishing the removal of silicon, manganese, and carbon. The lining of the furnace must therefore be of acid character. The basic process involves the use of a basic flux and the production of a basic slag, with removal of not only silicon, manganese, and carbon, but also phosphorus and a part of the sulphur. The lining is necessarily basic. Unlike the Bessemer process, which is used only as an acid process in this country, the open-hearth method is conducted both as an acid and as a basic process, but the basic process greatly predominates.

The open-hearth process differs from the Bessemer process in the strength of the deoxidizing agencies, and since the action is much less violent and rapid, requires a time of about ten hours as compared with about ten minutes. The furnace capacity is much greater than that of the converter, however, being from 50 to 200 tons.

The open-hearth furnace is charged with pig iron (either solid or molten) and scrap steel (always solid), and the operation of the process started by admitting a current of preheated gas and air which burn within the hearth chamber. Much heat is reflected from the arched roof and the walls. The oxidation of the impurities is a source of a certain amount of heat, but the greater part is derived from the combustion of gas fuel. A certain amount of ore is added during the process to provide additional oxides, and additional pig iron may be added if there is danger of the original carbon becoming low too early in the heat to maintain the required temperature until the end of the operation.

The furnace is tapped through a spout either by opening a tap-hole or by tilting the furnace, the spout in the latter case being located above the normal level of the bath of metal.

The Furnace and its Operation

89. General Features of the Regenerative Furnace. The great difference in principle between the puddling furnace and the air furnace on the one hand, and the open-hearth furnace on the other hand, lies in the utilization by the latter of the regenerative principle with gas fuel. By preheating the gas and the air used for combustion, by means of the heat carried out of the melting-chamber by the burned gases, a great increase in thermal efficiency is gained and the furnace temperature attainable is immensely increased.

The arrangement of a furnace to utilize the regenerative principle is shown by the diagram of Fig. 23. The melting-chamber or hearth is shown in the upper central portion of the figure. On either side are the openings called "ports," through which the gas and air enter the melting-chamber, and the vertical flues which lead to the regenerative chambers. Two regenerative chambers or "regenerators" are provided on each side of the furnace, the larger and outermost one being used to preheat the air required for combustion, while the smaller inner chamber is heating gas. Each regenerator is filled with a checker-work of brick through which the gas and air pass. Before starting up a cold furnace these regenerators are heated by fires built in the flues beneath.

Supposing that the gas and air valves are in the position shown in Fig. 23, the direction of circulation of the gases is indicated by the arrows. Gas enters the inner regenerator on the left-hand side and passes through the bricks of the checker-work, which give up a portion of their heat, raising the temperature of the gas.

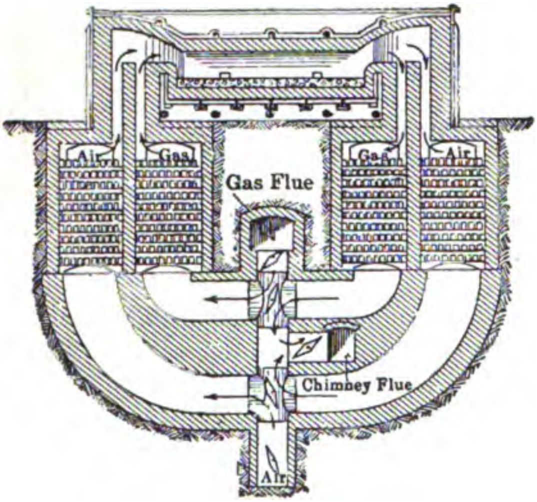


Fig. 23. — Diagram of Regenerative Furnace. (Stoughton.)

At the port the hot gas encounters the current of air which has been similarly heated in passing through the outer regenerator, mixes therewith, and burns within the melting-chamber. The burned gases are then caught by the stack draught and drawn out through the ports on the right-hand side. Passing downward through the regenerators, a large part of the heat of the gases is taken up by the checker-work, the upper portion of which attains a temperature of about 1000° C. (1832° F.). The gases leave the regenerators at a temperature which should not exceed 400° C. (752° F.), and pass through flues which lead to the stack.

By reversal of the valves the direction of flow of the air and gases may be reversed, so that, as soon as one set of regenerators begins to be cooled too much, the incoming gas and air may be sent through the other set, which has just been heated by the burned gases. By reversing the direction of the currents about every twenty minutes the temperature of the melting-chamber may be maintained at a fairly constant point, in the neighborhood of 1600° C. (2912° F.) to 1700° C. (3092° F.).

90. Construction of Open-hearth Furnace. Fig. 23 is simply a diagrammatic representation of a regenerative furnace, such a relative arrangement of flues, regenerators, and melting-chamber not being a practical one for actual use.

Two common forms of open-hearth furnaces find wide application in the steel industry. The earliest type is the stationary furnace. The tilting or rolling furnace is a comparatively recent development in furnace design and has been adopted in many important installations.

(a) *Stationary Open-hearth Furnace.* The melting-chamber is a rectangular structure built of brick masonry and supported upon either a solid masonry foundation or on beams and piers. It is reinforced with buckstays, bearing-plates, and tie-rods, and is lined with refractory material of suitable chemical nature to resist the attack of the materials which come in contact with it. The hearth is built in the form of a shallow dish and has a capacity of from 15 to 200 tons of metal.

If the furnace is intended for use in the acid process, the hearth is built of fireclay bricks overlaid with a layer of silica about 18 inches thick. The silica is applied as silica sand, which is spread in thin layers, each layer being exposed to the full heat of the furnace and brought to the sintering point before the application of the next layer.

The basic furnace is built of magnesite bricks overlaid with a mixture of calcined magnesite and about 10 per cent of anhydrous tar. The lining is placed in layers and burned in place as in the case of the acid furnace.

One or more large charging doors are provided in the front wall of the furnace just above the level of the top of the hearth lining, and an inclined spout leads from the lowest portion of the hearth to the back or pouring side of the furnace.

The side walls of the melting-chamber and the arched roof are made of silica bricks, the most refractory material that can be obtained, laid with almost no mortar in the joints. The roof is arched from front to back and its skewbacks are supported upon steel channels, which practically carry the weight of the roof independently of the side walls: In lining the basic furnace a layer of neutral chromite brick is usually placed between the silica bricks of the side walls and the basic hearth.

The ports are designed with great care in order that the flames may neither impinge upon the bath, thereby oxidizing it excessively, nor upon the roof, which would quickly be burned out. The gas ports are always located beneath the air ports, in order that the bath may not be oxidized excessively by direct contact with the air, and also to promote a better mixing of gas and air, since the gas is lighter and therefore rises. The masonry of the ports is built of silica bricks and the floor is commonly covered with a layer of neutral chrome ore. The port area required for air is about twice that required for gas.

In order to prevent the carrying of dust and slag into the regenerators, the vertical flues from the ports do not lead directly to the regenerators, but to chambers called "slag-pockets" which are located on a level with the regenerators below the melting-chamber.

The regenerators are very large in proportion to the melting-chamber, and are nearly filled with the checker-work of bricks which serves to absorb heat from the outgoing gases and preheat the incoming gas and air. The total open space through the checker-work must considerably exceed the area of the ports because of the friction offered to the passage of the gases. The flues beneath the regenerators are large in order to distribute the incoming gas and air uniformly, and several longitudinal walls are provided in the flues for the purpose of supporting the lower tiles of the checker-work.

(*b*) *Tilting or Rolling Furnaces.* The tilting or rolling furnace of the Wellman type is shown Fig. 23*a*, and Fig. 23*b*. The furnace consists of a heavy steel casing of rectangular form, lined with masonry like the stationary furnace, but mounted on two steel rockers which rest upon heavy bed-castings. Two large hydraulic cylinders on the pouring side of the furnace serve to rock the furnace forward or backward during the operation of pouring.

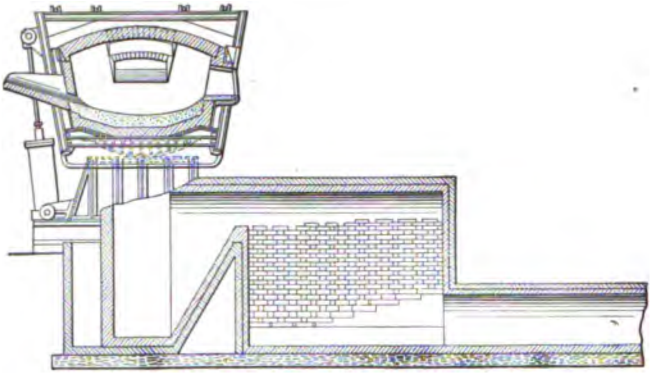


FIG. 23*a*. — The Wellman Tilting Open-hearth Furnace. Transverse Section.

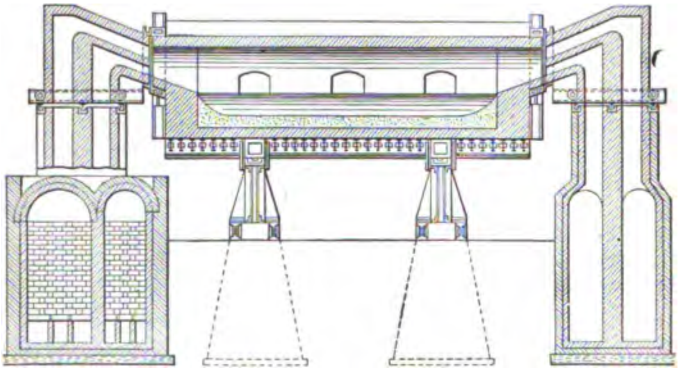


FIG. 23*b*. — The Wellman Tilting Open-hearth Furnace. Longitudinal Section.

The interior of the melting-chamber of the tilting furnace differs in scarcely any respect from that of the stationary furnace except that the spout is located above the level of the bath until the furnace is tilted on its rollers, and the design of the port opening is different. A cast-iron water-cooled ring is fitted around the port openings on the outside, and matches a similar ring on the port. The ports are built inside a heavy steel framework and are mounted on wheels or tracks carried by the up-takes from the regenerators. When it is desired to tilt the furnace, the ports are drawn back away from the furnace ends and, since the port openings are exposed while the furnace is in its tilted position, the gas and air supply must be stopped during the operation.

A common adjunct of the rolling furnace is the "fore-hearth," a substitute for a teeming ladle, which is bolted on in place of a pouring spout on the back of the furnace. The fore-hearth resembles a teeming ladle in its design and is provided with two teeming valves through which the metal is discharged into ingot molds while the furnace is in its pouring position.

The design and arrangement of the slag-pockets, regenerators, valves, and flues for the rolling furnace differs in no essential respect from that of the stationary furnace above described.

91. Stationary vs. Tilting Furnaces. The stationary furnace is less complicated in its design and requires less elaborate equipment for its operation. It is less expensive to install, and the cost of its upkeep is much less. On the other hand, the tilting furnace has the advantage of never causing delay and consequent oxidation of the bath, owing to difficulty in clearing the tap-hole; the slag can be poured off at any time, which is a great advantage in the basic furnace especially; repairs to the hearth bottom may be made with much greater facility between or even during heats; metal may be poured off at any time and transferred between furnaces; and boiling and violent action during pouring is lessened by the chilling of the metal caused by the entrance of cold air through the open ports.

92. Life of Furnace and Repairs. The life of the open-hearth furnace is extremely variable, depending upon the quality of the materials used and the management of the furnace. The ports are usually the first portion to become excessively injured and often need replacement long before the furnace must be entirely rebuilt. The removable ports of the tilting furnace have a special advantage on this account.

The bottom usually requires repairs in spots between heats, and is more extensively repaired during temporary shutdowns. In this way this bottom lasts almost indefinitely.

The roof of the furnace fails sooner or later by burning through in spots or by falling in. When this happens the furnace must be practically rebuilt.

The regenerators finally give out, either by becoming choked up with dust, or by cracks opening up in the walls. A shutdown is required in either case.

In general the life of a furnace is from 200 to 600 heats, or from three to six or eight months' operation. The acid furnace lasts longer, from 800 to 1200 heats, or from ten to sixteen months.

The Furnace Fuel

93. Natural-gas Fuel. Natural gas is the ideal fuel for the operation of the open-hearth furnace, but its use is necessarily limited to localities where it is available.

94. Producer Gas. Only one form of artificial gas is of any importance in steel-making, this one being producer gas.

The modern gas producer is a cylindrical shell of steel, lined with firebrick. Coal is charged into the hopper at the top and the cover is closed before the bell is lowered to discharge the contents into the producer. A supply of air, insufficient for complete combustion of the coal, is admitted through openings in the wind-box below the grates, and also through the pipe in the center. A steam injector is used to draw in the air. The ash falls through the grates into the ash pit, which is filled with water into which the shell of the producer projects, thus forming a water-seal.

The air admitted through the grates of the producer converts a part of the carbon of the fuel to CO_2, which is reduced to CO in passing upward through the incandescent bed of fuel. The carbon monoxide is diluted by the nitrogen of the air introduced and somewhat enriched by the hydrogen of the decomposed steam and other moisture present. The actual ultimate composition of producer gas is variable, but averages about 61 per cent N, 20 to 25 per cent CO, 6 to 10 per cent H, 3 to 8 per cent CO_2, and 2 to 4 per cent methane.

The Basic Open-hearth Process

95. General. The basic open-hearth process, like the basic Bessemer process, differs from the acid process mainly in that it utilizes stock higher in phosphorus and sulphur, and a basic slag must be produced by the addition of strong bases to the charge in order to effect the removal of this excess phosphorus and sulphur. In order to resist the corrosive action of the basic slag the hearth must be lined with basic material, but the hearth lining, whether acid or basic, plays no part in the purification of the iron.

96. The Furnace Charge. Operating Practice. Basic open-hearth practice is characterized by a number of quite distinct modifications, depending upon the choice of materials which constitute the furnace charge. The resulting processes are characterized as:

The pig-and-ore process.
The pig-and-scrap process.
The all-scrap process.

The pig iron used must contain from 1 to 2½ per cent phosphorus, less than 1 per cent of silicon, and at least 1 per cent of manganese. The carbon will usually run from 2.5 to 3.5 per cent. The pig iron may be charged either solid or molten.

The substitution of scrap iron for pig iron results in shortening the time required for the operation, since there will be a lower percentage content of impurities to eliminate. When the pig iron is entirely replaced by scrap in the "all-scrap process," there is insufficient reducing material present to prevent excessive oxidation of the iron in melting, and it becomes necessary to use some form of carbon to supply the need for a reducing agent.

In the "pig-and-ore process" the charge is principally pig iron, to which ore is added in order to hasten the process. The limiting amount of ore is reached when the boiling of the charge becomes excessive. Unless pig iron is cheaper than scrap, the pig-and-ore process is not a commercially practicable one. Molten pig iron is often used in this process, the iron being poured in on the ore, which has first been charged. A mixer is commonly interposed between blast furnace and steel furnace as in the Bessemer process.

The "pig-and-scrap" process is now the most usual process, the average practice being to use about 50 per cent of each material, the exact proportions used in a given case being largely a question of relative costs. Very commonly a small proportion of ore or mill scale is added to hasten the process.

The order of charging varies, but the usual method consists in charging first a small quantity of small scrap to protect the hearth, after which the lime flux and the ore or mill scale are charged upon the scrap. Most of the balance of the scrap and about one-third of the pig are now charged and the furnace started. The balance of the scrap and the pig is added after an hour or two, when the former charge has melted down to make room.

The flux used is commonly lime, the amount required being dependent upon the contents of phosphorus, and especially sulphur, in the charge. High silicon also increases the amount of lime required in order to render the slag basic. In general the charge of lime amounts to from 10 to 30 per cent of the total charge, and the resulting slag contains from 35 to 45 per cent of CaO.

97. Chemistry of Basic Process. Melting on the basic hearth is attended by oxidation of the metalloids, the most easily oxidized ones being eliminated first. The silicon, manganese and carbon are all considerably reduced in amount during the period of melting (the first four or five hours). The phosphorus, however, remains practically unaffected until the end of this period, when it begins to be rapidly oxidized.

It is necessary, in order to prevent the bath from becoming too cool and to prevent oxidation of the iron toward the end of the operation, to eliminate the carbon last. If the carbon is disappearing too early it is the practice of the melter to add pig iron to provide additional carbon. Sometimes, when the phosphorus burns out rapidly, and the carbon too slowly, it is necessary to hasten the oxidation of carbon by adding ore. The progress of the operation is tested from time to time by ladling out a small amount of metal, casting a small test billet, breaking it, and examining the fracture. Billet tests are usually supplemented by chemical analysis of frequent samples.

The slag performs several very important offices in the operation of the basic hearth. Its chief function is to take up and retain the oxides of the metalloids — silicon, manganese, phosphorus, and sulphur. It must also act as a protection to the bath from excessive oxidation by the furnace gases, and, by virtue of its contained oxides, assist in the oxidation of the impurities. For efficient action as a deoxidizing agent it must be very fluid in order that it may mix intimately with the bath.

The slag must also be rich in bases in order to retain the oxides of phosphorus and sulphur, and the removal of sulphur is greatly facilitated if the slag is rendered still more strongly basic by the addition of calcium fluoride just before the end of the operation. No oxides, such as ore or scale, can be added toward the end of the operation, lest the final slag be an oxidizing one, resulting in the metal being full of oxides and therefore turbulent when poured and very unsound after solidification.

98. Recarburization. Recarburization of basic steel cannot be accomplished in the furnace because the carbon, silicon, and manganese of the recarburizer would reduce the phosphorus in the slag and restore it to the metal.

On this account the recarburizer, in the form of ferro-manganese, together with coal, charcoal, or coke, is added to the stream of metal as it flows into the ladle. Provision is made for the removal of the greater part of the slag by overflowing at the top of the ladle. Spiegeleisen is not used as a recarburizer, because it must be used in a molten state and a cupola could not be operated to supply it in proper condition at the infrequent intervals at which a recarburizer is required in open-hearth operation.

Low-carbon steel is always poured only after the carbon has been reduced to about 0.10 or 0.15 per cent, the additional carbon required being added by the recarburizer. High-carbon steel is preferably handled in the same way, but it is cheaper and takes less time simply to reduce the amount of carbon slightly below the desired point, and then recarburize. The latter method is often used, but entails the danger of pouring steel while it is still too high in phosphorus and in oxides which cause unsoundness of the ingots.

99. Pouring the Ingots. The steel is discharged from the pouring spout or tap-hole of the furnace into a teeming ladle or fore-hearth, from which it is teemed into ingot molds mounted on cars. The ordinary open-hearth ingot may weigh as much as 10 tons and is therefore much larger than the usual Bessemer ingot.

THE ACID OPEN-HEARTH PROCESS

100. General. The acid open-hearth process differs from the basic open-hearth process principally in the character of the iron used, the omission of the flux, and the time required for the operation. Since the slag formed is acid, it is unable to retain oxides of phosphorus and sulphur, and a pig low in these elements is required. An acid lining ot the hearth is required to prevent rapid corrosion by the acid slag. The time required for the operation is shorter than that for the basic process because the iron contains less impurities to be removed, because the process need not be prolonged to remove phosphorus, and because no part of the heat is consumed in melting and accomplishing the function of the flux.

101. The Furnace Charge. The charge of the acid furnace usually consists of approximately one-third pig iron and two-thirds scrap. The pig iron is fairly low in silicon, and low in manganese, phosphorus, and sulphur. The usual limits of composition are from 0.8 to 2.0 per cent silicon, 0.3 to 0.5 per cent manganese, and less than 0.05 per cent of both phosphorus and sulphur. The carbon content will be from 3.0 to 4.0 per cent.

The scrap will be of variable composition, but will average about 0.2 to 0.3 per cent carbon, 0.1 to 0.3 per cent silicon, 0.4 to 0.8 per cent manganese, and less than 0.05 per cent of both phosphorus and sulphur.

Ore is not usually initially charged in the acid furnace, but may be added during the process for the sake of increasing the oxidizing agencies to hasten the removal of carbon. The pig iron is charged into the furnace before the scrap in order to prevent the scorification of the hearth, which would occur if scrap were charged first.

102. Chemistry of Acid Process. The melting operation is in the main an oxidizing action, though the flame may be a comparatively reducing one during charging in order to prevent excessive oxidation of the pig iron and, more particularly, the scrap during this stage.

The metalloids are largely eliminated during the melting-down stage, which requires some three or four hours, the silicon usually disappearing first, closely followed by the manganese. The amount of carbon oxidized during melting is dependent largely upon the amounts of the more easily oxidized elements (silicon and manganese) present. The lower the content of the latter elements, the greater will be the proportion of carbon oxidized. In any event two-thirds of the carbon will be removed very soon after the charge is altogether melted. The balance will be oxidized only very slowly, its disappearance usually being accelerated by the addition of ore to the bath. The slag in the acid process never constitutes the important oxidizing agency that it does in the basic process.

103. Recarburizing. Recarburizing in the acid process is accomplished in the furnace, rather than in the ladle, because the considerations which prevent recarburization in the basic furnace are not here operative. The practice as to the degree of recarburization varies, but in general the carbon is reduced to the practical minimum in the case of mild or medium steel, and the recarburizer added twenty to forty minutes before the heat is tapped. In the case of melting for high-carbon steel the carbon is usually reduced only slightly below the desired amount before the recarburizer is added. In this event, the addition to the bath is rather more a deoxidizer than a recarburizer, the primary object being the restoration to the bath of iron which has become oxidized. The recarburizer or deoxidizer is, in this process, ferro-manganese and ferro-silicon, as a rule. Coal is sometimes added in the ladle as in the basic process. The addition of the recarburizer necessarily largely increases the content of silicon and manganese in the steel, as well as the carbon content.

SPECIAL OPEN-HEARTH PROCESSES

104. Duplex Processes. There are several methods by which the acid Bessemer and the basic open-hearth processes may be combined in a so-called "duplex process," whereby the silicon, manganese, and part of the carbon are eliminated in the converter, the phosphorus and the remainder of the carbon being removed in the open-hearth.

In one duplex process the pig iron is blown in the acid converter until the silicon and manganese are practically eliminated and the carbon reduced to about 1 per cent, after which the converter charge is transferred to a mixer and thence to the basic open-hearth, wherein the phosphorus and the remainder of the carbon are removed.

In another method the Bessemer blow is continued till the carbon is reduced to only a few tenths of 1 per cent, after which the product is transferred to the open-hearth, mixed with a large proportion of pig, generally molten, and the process completed exactly as in the case of the latter part of the ordinary pig-and-scrap process.

The advantage of the duplex process over the Bessemer process lies in the fact that lower grade, high-phosphorus pig iron may be used and yet produce a satisfactory grade of open-hearth steel.

The advantages of the combined process over the open-hearth process are the saving of about one-half of the time ordinarily required in the open-hearth, and the saving effected in cost of renewals of the hearth lining, because of the fact that the silica is removed before the metal enters the hearth.

105. The Talbot Process. The Monell Process. The Talbot process is a modification of the basic open-hearth process, whereby the hearth is worked continuously. The tilting furnace must be used, and the depth of bath is twice that ordinarily employed. The capacity of the furnace may exceed 200 tons.

The furnace is charged and conducted in the usual manner for the pig-and-ore process (no scrap being used), until the carbon is reduced to the desired point. The slag is then poured off and about one-third of the steel is poured into the ladle, recarburized, and teemed. Iron ore and limestone are now added to the bath to form a new slag, and molten pig iron is poured in to make the charge equal to its original amount. Oxidation proceeds very rapidly, owing to the large amounts of iron oxide in the slag. The interval between the addition of pig and the pouring of steel is only from three to six hours, and three to four heats are poured per day.

The principal advantages of the process are the large tonnage produced and the excellent temperature control possible. The furnace is expensive, however, both to build and to maintain.

The Monell process is another modification of the basic open-hearth process, wherein a very strongly oxidizing slag is prepared before molten pig iron is charged. The slag is produced by melting limestone with ore or other iron oxide equal to about one-fourth of the pig-iron charge. Molten pig iron is poured into this slag and oxidation proceeds with extreme rapidity, most of the silicon, manganese, and phosphorus being eliminated within one hour. The balance of the process is exactly similar to the ordinary pig-and-scrap process, and the total time required is about the same.

ELECTRIC REFINING OF STEEL

106. Electric Refining Processes in General. The part which electricity plays in the various electric steel processes is simply that of a source of heat. Slags, which are strongly oxidizing in character, must be added to the bath in order to effect any refinement. In practice, the slag used is a strongly basic iron-oxide slag, because such a slag will oxidize phosphorus as well as retain the oxide formed. If much phosphorus is to be removed, or if it is to be reduced to a very low point, it is necessary to use two slags, skimming off the first after it becomes highly phosphorized.

Sulphur can be reduced only by removing the iron-oxide slag, after the elimination of phosphorus, and producing a slag that is made up almost entirely of lime. The presence of manganese favors the removal of sulphur, because manganese sulphide is more readily taken up by the slag than iron sulphide, thus making possible the formation of calcium sulphide, in which form the sulphur is retained in the slag.

One of the greatest advantages of electric refining processes lies in the fact that dissolved gases, occluded oxides, etc., are readily removed from the steel through the agency of heat alone.

107. Types of Electric Refining Furnaces. Three quite distinct types of electric steel refining furnaces have been developed to the point of practical commercial application.

Furnaces employing an open arc between electrodes above the bath, the latter being heated by radiation alone.

Furnaces employing an arc between electrodes and the bath, the latter forming a part of the electric circuit. The metal is heated largely by conduction from the slag bath, which carries much of the current and is heated both by radiation and by reason of its electrical resistance.

Electric induction furnaces, wherein the bath forms the secondary of a transformer consisting of a closed circuit with but a single turn.

108. Open-arc Furnaces. The Stassano furnace is a type of open electric-arc furnace. Its general arrangement is shown by Fig. 24. The working chamber is a cylindrical structure, lined with basic refractory brick, mounted upon a circular track at a slight inclination from the vertical, and slowly rotated in order to increase the mixing effect.

Electric energy is converted into heat through the medium of an arc between carbon electrodes just above the level of the bath, the bath being heated by radiation. Three-phase alternating current is used, three electrodes being necessary. Any grade of scrap or pig may be used, and the refining carried to any desired degree, the steel produced being comparable to best crucible tool steel in quality. The maximum capacity of the Stassano furnace is about 5 or 6 tons of metal per heat.

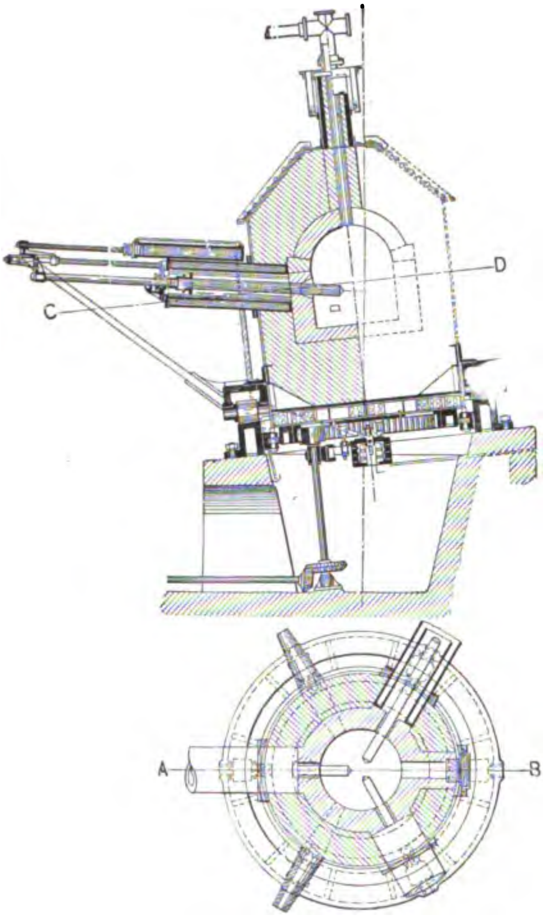


FIG. 24. — Stassano Open-arc Electric Furnace.

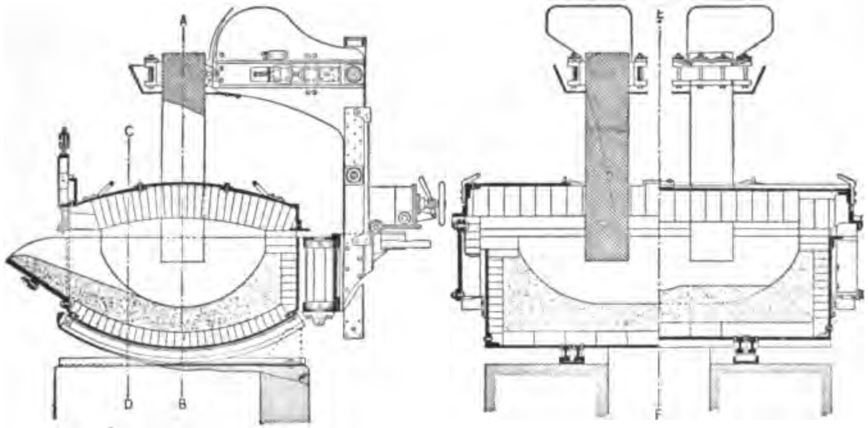
109. Arc-resistance Furnaces. The Héroult electric furnace which illustrates this type resembles closely the open-hearth furnace except that heat is supplied by electrical means instead of by the combustion of gas fuel. The form of the furnace is shown by Fig. 25.

Current enters through one of the electrodes which are suspended above the bath, arcs to the charge through which it passes, and thence arcs to the negative electrode.

The Héroult furnace may be used to refine any grade of scrap, but its most important applications have been in conjunction with Bessemer converters and with the open-hearth in duplex units. The metal is, in this case, brought in a molten state from the converter or from the open-hearth, and practically any desired grade of steel may be produced. Superior grades of rail steel, axle steel, steel for wire, steel for castings, tool steels, and special alloy steels have been made with great success by refining either Bessemer or open-hearth metal in the Héroult furnace.

The capacity of the Héroult furnaces is about 15 tons of metal, and the refining of Bessemer metal has been carried on for weeks at the rate of twelve to fifteen heats per day, meaning a daily output of about 180 tons of super-refined steel.

110. Induction Furnaces. The electric induction furnace differs radically in theory and design from the furnaces employing electrodes. The induction furnace is in principle simply a stepdown transformer, wherein the metal under treatment forms a closed secondary circuit.



TRANSVERSE SECTION-E-F

(A-B)-LONGITUDINAL SECTION-(C-D)

FIG. 25. — Héroult Arc-resistance Electric Furnace.

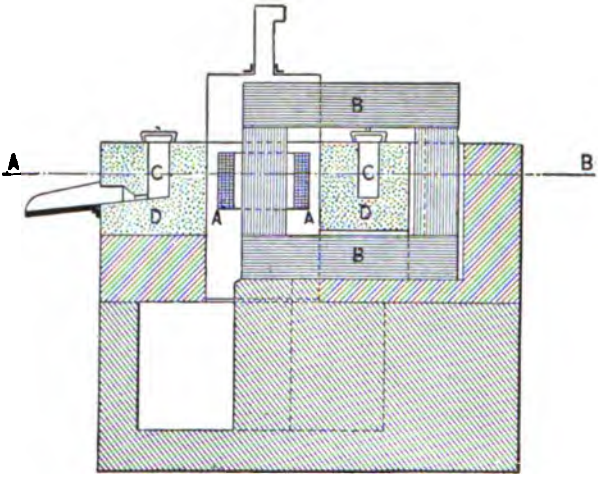
A simple form of induction furnace is the Kjellin furnace shown in Fig. 26. The primary coil, through which high-voltage alternating current is passed, is shown at *AA*; the magnetic core of laminated iron, in which an alternating current is induced by the primary, is shown at *BB*; and the bath of metal under treatment shown at *CC* (contained in the circular crucible *DD*, built of calcined magnesia or dolomite) forms the secondary in which current is induced by the magnetic core. The resistance offered by the molten metal to the passage of the induced current is the source of heat whereby any desired degree of refinement may be accomplished.

This furnace ranks high as to thermal efficiency, but its use is limited to rather small capacities because of the limited contact area between slag and metal, which means slow refining. Few furnaces of this type have been built with capacities exceeding ½ ton, and its principal application has been in the refinement of metal for tool steel. If the metal charged is not already molten, a portion of each charge must be left in the crucible to establish a complete circuit until the solid metal has been melted down.

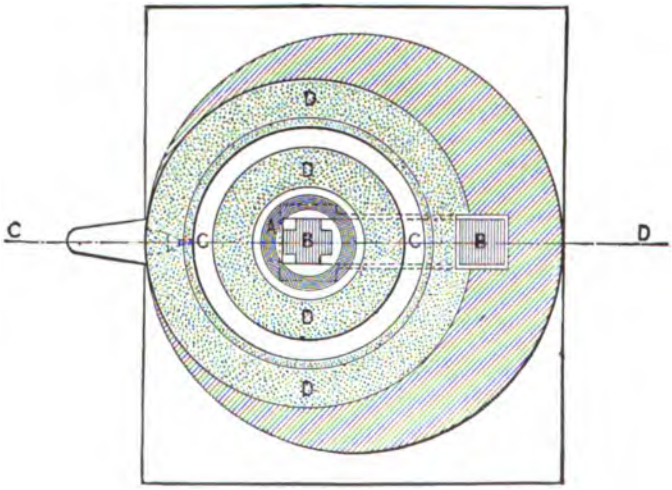
111. Applications and Limitations of Electric Furnaces and Electric Refining Processes. The electric furnace is able to make tool steel of crucible quality at a lower cost than the crucible process. In the field of steel castings it has also a considerable advantage over the highest grade crucible-made castings in the matter of cost, though it cannot compete with the open-hearth in the production of lower-grade castings.

The electric furnace is not a competitor of the Bessemer converter and the open-hearth in the production of mild and medium steel of ordinary quality. It is an important adjunct of both of these processes, however, taking their product and super-refining it to produce steel for special purposes.

In the production of special alloy steels, the electric furnace has a special advantage over other steel processes in that it need not be operated under oxidizing conditions, but may be worked under either neutral or reducing conditions. This is an important consideration in using certain valuable alloying elements which are very easily oxidized and lost in other furnaces.



SECTION C-D



SECTION A-B

Fig. 26. — Kjellin Electric Induction Furnace.

ROLLING MILL OPERATIONS

112. Necessity for Reheating. An ingot cannot be sent to a rolling mill and rolled immediately after the ingot mold has been removed, because at that time the interior is still molten. If, on the other hand, the ingot is allowed to stand until the interior has solidified, the exterior will be too cold to be worked. It is therefore necessary to place the ingots, immediately after stripping, in a furnace where the interior may be solidified and the exterior kept at the required temperature for working.

The process of rolling finished steel sections from ingots is a protracted operation, necessitating a great many passes of the metal through the rolls. It is necessary, at one or more stages in the reduction of the section, to reheat the bloom or billet or slab which has been formed by the initial reduction of the ingot, when it has cooled below the proper working temperature.

Two classes of reheating furnaces are therefore a necessary part of the equipment of a rolling mill: first, a furnace for heating ingots, or at least equalizing their temperature, and second, a furnace wherein billets or unfinished shapes may be reheated at any stage in the process of rolling.

113. Reheating Furnaces. There are three principal classes of reheating furnaces: the "soaking pit" and the regenerative gas-fired pit-furnace for ingots, and continuous furnaces for billets and other small sections. Special types of reheating furnaces are also required for reheating large blooms and slabs.

The original soaking pit is simply a masonry chamber, built below the floor level, and charged through the top in order that the ingots may remain vertical while solidifying. No fuel is employed, but the ingots are stripped and placed in the soaking pit as soon as possible after teeming, the heat of the still molten interior of the ingot being depended upon to bring the exterior to the proper temperature.

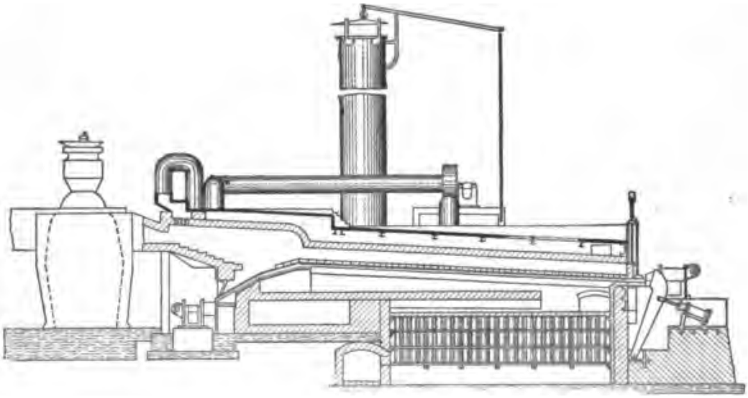


FIG. 27. — Gas-fired Recuperative Billet Heating Furnace.

The regenerative gas-fired pit-furnace is also a vertical furnace, built below the floor level, and charged through the top. Gas fuel is burned within the heating chamber.

Billet-heating furnaces are now commonly of the reverberatory type, gas-fired, and recuperative in principle. Such a furnace is shown in Fig. 27. The billets are charged at the cool end of the furnace, and are pushed along through the length of the furnace by an hydraulic ram mounted at the charging end. Water-cooled pipes laid in the bed of the heating chamber and extending throughout its length provide a sort of track along which the billets are pushed. The billets encounter hotter temperatures as they approach the end where the gas and air ports are located, and are there discharged and conveyed back to the rolls. The burned gases, upon leaving the heating chamber, are caused to pass through a series of pipes in a chamber below the working chamber, and the air which is to be used for combustion is caused to circulate through this chamber, thus becoming preheated.

114. Rolling Mills. The most essential parts of a rolling mill are the rolls. Cast-iron rolls, which have been chilled to produce a hard exterior, and turned in a lathe to produce a smooth surface of the desired form, are very commonly used, especially for finishing rolls. High-carbon steel is also used when the rolls must be very strong, and even nickel-steel rolls have been used. All of the rolls except those used for finishing have their surface roughened in order to increase their grip on the metal.

Rolls are turned in an infinite variety of shapes, varying from the plain cylinders used for plates and some rectangular shapes to the rolls used for structural shapes, rails, corrugated bars, etc., which may be quite intricate in form. All rolls except plain cylindrical rolls make provision for several passes of the metal, each pass approximating the final form of the section desired more closely than the last.

Rolling mills may be in general classed under one of three heads: "two-high" mills, "three-high" mills, and "universal" mills.

Two-high mills consist of a single pair of rolls mounted in the same vertical plane. One variation of the two-high mill is the "pull-over" mill, whose rolls always run in the same direction, so that the metal after each pass must be pulled back over the top of the rolls to be fed in for the next pass. This is the simplest form of mill and the cheapest, but its operation is slow, and it is adapted only for rolling small shapes which can be readily handled. A more important type of two-high mill is the "reversing" mill, the rolls of which may be made to run in either direction by reversing the engines which drive them. Successive passes are therefore made in opposite directions through the rolls. The two-high reversing mill is often used in "cogging" ingots.

The *three-high mill* has three rolls geared together, so that the metal may make one pass between the lower and the middle roll, and the next pass in the opposite direction between the middle and upper roll, without reversing the rolls. A very large proportion of all steel shapes are rolled or at least finished by a three-high mill.

The *universal mill* is provided with two auxiliary rolls mounted vertically just in front of the horizontal rolls. The distance between the axis of these rolls is adjustable horizontally and they are designed simply to keep the edges of the metal smooth without effecting any reduction. Universal mills are made with vertical rolls on only one side of the horizontal rolls or on both sides, and they may be either two-high or three-high mills.

All rolling mills which handle anything except very light material must be provided with a series of rollers in front of and behind the rolls, known as the "roll tables." The roll tables for three-high mills must be capable of being raised or lowered at the end next the rolls, in order that the metal may be directed between either the upper or the lower set of rolls.

The sketches of Figs. 28, 29, and 30 illustrate the application of three-high mills in the cogging of ingots and the rolling of special shapes.

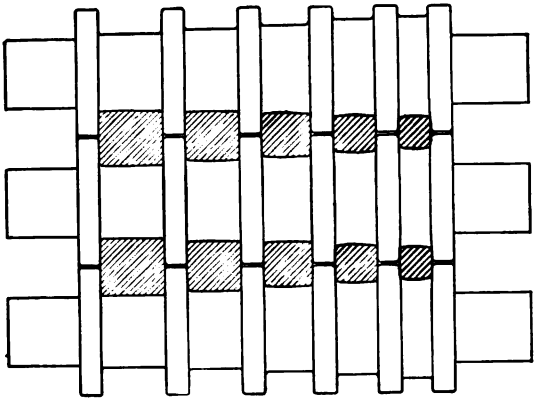


FIG. 28. — Cogging Rolls.

115. Examples of Rolling Practice.

Steel Rails are rolled by a process whose general features are as follows:

The ingot, after reheating in a pit furnace, is cogged down to a bloom whose cross-sectional dimensions are about one-half those of the original ingot. This operation is accomplished by a series of about 8 or 10 passes through a set of cogging rolls whose form is that shown by Fig. 28. The bloom is now sheared at each end to remove the pipe and the ragged end formed by the rolls, cut in two in the center, returned to the reheating furnace, and brought again to the proper temperature for rolling. The next series of 4 to 6 passes are made in one or more trains of roughing rolls (Fig. 29), and the last 8 or 10 passes in a train of finishing rolls (Fig. 30). (The figures here given are merely representative of average practice. The number of passes in each roll train varies considerably in the different rail mills.)

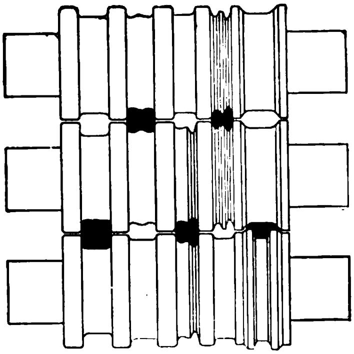


FIG. 29. — Roughing Rolls.

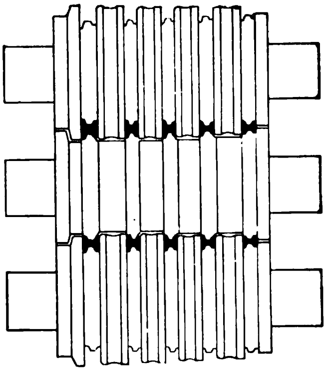


FIG. 30. — Finishing Rolls.

Structural Steel Sections are rolled in the same manner as rails. The different sectional areas for a given size of any structural shape such as angles, I-beams, channels, etc., may be produced with the same set of rolls by simply changing slightly the axial distance between the finishing rolls.

Plates are cogged from the ingot. The resultant slab is sheared into smaller slabs, and the pipe discarded, the slabs are reheated and the rolling completed. The successive reduction in the thickness of the plate is accomplished by bringing the rolls slightly nearer together between passes. Plates that are rolled in an ordinary mill and then sheared are known as sheared plates. Plates rolled in a universal mill are known as universal mill plates.

Rods are rolled in a manner similar to that described for steel rails except that the original bloom is usually cut up into a number of small sections before reheating and rolling. A mill called a "guide mill" is used, the material after each pass being bent around and guided into the next pass by a device specially attached to the mill for the purpose.

Wire-making is only a rolling operation so far as the making of the wire-rod is concerned. A considerable portion of the reduction of the section is accomplished by a special operation known as "cold-drawing." The wire rod is rolled in the manner above noted, its final diameter being usually from ¼ to ½ inch. The wire rod is then wound into coils and pickled in a dilute solution of sulphuric acid, which removes the scale. Water is next sprayed on to wash off the acid, and this is followed by immersion in a bath of limewater, which removes the last traces of acid. The coils are now dried in an oven and sent to the wire-drawing mill.

Cold drawing consists in successively reducing the section, and extending the length, by repeatedly pulling it cold through tapered holes in a die or "draw-plate." Each hole through which the metal is drawn is somewhat smaller than the preceding hole, the average amount of reduction being from 20 to 25 per cent. Some thick lubricant is applied to the draw-plate to reduce friction and prevent too rapid wear on the hole.

The wire must be annealed by heating to a low red heat in a closed receptacle after each 3 to 10 passes, because of the hardening of the metal caused by drawing. The finished wire is also annealed unless it is to be sold as hard-drawn wire.

Lap-welded Pipes. The metal is first rolled into flat strips called "skelp," of the desired thickness, then bent to a U-shaped section and, by another pass, to a circular section with the edges overlapping. (Small pipe may be bent to the circular section by drawing the skelp through a die.) The metal is now brought to a welding heat and is passed through a pair of welding rolls over a "mandrel" which is supported between the rolls on the end of a long rod. A second pass through "sizing" rolls is made to insure accuracy of size.

Butt-welded Pipes are made by drawing the skelp at a welding heat through a die or "bell" which welds the edges together without lapping.

Seamless Tubes (small sizes only) are made either by forcing a flat plate through a cylindrical die by means of a mandrel, or by piercing a billet longitudinally, expanding the hole by forcing larger and larger tapered expanders through it, and finally rolling over mandrels until the section desired is attained.

Cold-rolled Steel is steel the last pass of which through the rolls is made with comparatively cold metal. Pickling is necessary before cold rolling to remove the scale, and the result is a great gain in accuracy in size and form, and in surface finish

Finishing Steel by Steam Hammer and by Presses

116. Forging under the Steam Hammer. In the early days of the steel industry the steam hammer was the principal means whereby steel ingots were worked up into the desired final form; but as ingots became larger and heavier, the hammer was to a great extent replaced by rolls which, although they do not work the metal so well, are much more rapid in operation and involve less expense for labor and for reheating.

The steam hammer now finds little application in the steel industry except in the forging of high-grade steel where the value of the product and the especial desirability of giving the metal the fine grain attained by hammering justifies the higher cost and in the production of that large class of articles called "drop-forgings." This class of articles includes a great variety of machine parts, small tools, automobile parts, etc.

Drop-forgings are made by the use of dies, between which the metal is worked into the desired form by the blows of a steam hammer. The dies are made of hardened steel, the impressions formed in the faces of the dies corresponding to the impressions formed in the mold for a casting. The metal is placed upon the lower die, which is made fast to the anvil, and the upper die is carried by the head of the hammer. Very often a series of dies are necessary to complete a forging, each set approximating more closely the final form required.

117. Forging by Means of Presses. The effect of pressing steel, by the action of large hydraulic presses, differs from that produced by the action of a hammer, in that the force applied acts for an appreciable interval of time, and the distortion produced extends deeper into the metal. In consequence, the press produces a better crystalline structure than does the hammer for all except very thin sections, and is therefore used in preference to the hammer for all heavy forging.

The hydraulic press consists essentially of a hydraulic cylinder in which a plunger or ram moves vertically, and is forced down upon the metal supported on an anvil block or bed as in the case of hammers. Presses vary in size from a few tons capacity up to 14,000-ton armor-plate presses which will handle ingots weighing 50 tons or more.

In addition to their use in the reduction of ingots in place of a cogging mill, and in the pressing of heavy plates, hydraulic presses are largely used in the production of forgings pressed between dies, as in the case of the steam hammer, and also in the production of a large class of articles made of thin plate steel which is pressed cold between dies

DEFECTS IN INGOTS AND THEIR CORRECTION

118. Blow-holes, Piping, Ingotism, and Segregation. One of the greatest sources of trouble for the steel-maker is the occurrence of *blow-holes*, which are almost unavoidably formed in some degree while the metal is solidifying in the ingot mold. Blow-holes are caused by the presence of gases such as hydrogen, nitrogen, and oxygen which are held in solution by the metal when molten but released as the metal solidifies, and they are also caused by the presence in the metal of iron oxide, which upon encountering carbon, forms CO gas.

The gas in blow-holes is usually reducing in effect and therefore the surfaces of the holes do not become oxidized and will weld together when the ingot is subjected to pressure in the operation of rolling or pressing. Blow-holes near the surface of an ingot, however, are apt to break through to the exterior, allowing oxidation and preventing perfect welding in the rolls.

Another defect in ingots, which cannot be corrected in rolling, is the occurrence of the *pipe* or shrinkage cavity which forms during solidification. Since the metal cools first in contact with the walls of the mold, the interior will remain molten after an outside solid shell has formed. The interior metal contracts as it solidifies progressively from the outside inward, causing the formation of a cavity which becomes filled with gases evolved during solidification. Since the hottest metal is at the top of the ingot, the upper portion remains molten longer and acts as a feeder to fill the shrinkage cavity in the bottom portion. The pipe is thus localized in the upper third of the ingot. This portion must be cut off in the rolling mill and goes back to the steel furnace as scrap.

Ingotism, the formation of large crystals of steel, caused by too slow cooling or casting at too high a temperature, is a serious defect in ingots which causes the steel to be weak and low in ductility. The bad effects of ingotism may be largely or entirely corrected by careful rolling or forging. The compression of the metal crushes and reduces the size of the crystals, imparting to the steel a much superior degree of strength and ductility. Care must be taken in the initial rolling or forging to avoid the formation of cracks which cannot subsequently be welded up.

Segregation of the impurities in steel ingots is caused by the fact that most impurities, notably carbon, phosphorus, and sulphur, are less soluble in iron when solidified than while molten. In consequence, a part of the impurities in the iron are progressively rejected by each layer of metal as it solidifies, being absorbed by the still molten portion, the net result being a tendency toward concentration of the impurities in that part or parts of the ingot which solidify last. Segregation cannot be altogether prevented, but it may be lessened by the addition of elements such as aluminum or titanium, which have the effect of quieting the steel. Casting in narrow ingots is also effective, but is not practicable in all cases because it would take so long to cast many small ingots from one large ladle that the first metal would be too hot if the last metal were not too cold.

THE HEAT TREATMENT OF STEEL

Practice of Hardening, Tempering, Annealing, and Case Hardening

119. General. If steel containing 0.6 per cent or more carbon be heated to a bright red heat and then rapidly cooled, as by plunging into water, it becomes very much harder, but at the same time much more brittle. If the hardened steel be heated to a temperature between 200° C. (392° F.) and 300° C. (572° F.) it will become softened or "tempered" and the brittleness largely removed, the degree of softness being directly dependent upon the temperature of tempering. If the steel is heated to the hardening temperature and then cooled very slowly it will be "annealed," i.e., rendered as soft as that particular steel can be made to be.

120. Hardening Steels. Every carbon steel possesses a certain critical range of temperatures within which important molecular changes occur in cooling. In general this range is from a low yellow down to a dull red heat. From about 900° C. to about 690° C. (1652° F. to 1274° F.) for steels containing sufficient carbon to harden usefully.

These molecular changes do not take place instantly, and they will therefore be retarded by shortening the time of passing through the critical range of temperatures. The amount of retardation is directly dependent upon the rapidity of cooling. If the cooling could be made instantaneous a maximum degree of hardness would be obtained, and lesser degrees of hardness are obtained by various rates of cooling after having heated the steel to just the proper temperature. For instance, some degree of hardening is obtained by quenching in molten lead; a greater degree by quenching in heavy oil; water makes it harder still; and so on, extreme hardness being obtained by quenching in ice-water. In all cases the degree of hardening obtained by any treatment will be dependent upon the amount of carbon present, and other elements, such as manganese, chromium, tungsten, etc., have not only a marked effect upon the hardness obtained, but they may greatly change the location of the critical range of temperatures, in some cases reducing it below atmospheric temperatures so that hardening may be accomplished by air-cooling.

121. Tempering Steels. Hardened steel is too brittle and too fragile for most uses without some degree of "tempering." The fact that tempering may be accomplished at temperatures far below the critical range is due to the circumstance that hardened steel is in a state of unstable equilibrium. It does not change its state simply because of the rigidity and immobility of the material, which does not allow sufficient molecular freedom for the alteration to take place. Only a relatively low degree of heating is sufficient to materially decrease this rigidity and increase molecular activity, resulting in a degree of loss of brittleness and hardness in proportion to the temperature attained, and, to a lesser extent, in proportion to the time allowed at that temperature. Very often the steel is again quenched after the desired tempering heat is reached in order to prevent overheating by heat conducted to the hardened portion from the balance of the piece.

The degree of heating in tempering carbon steels is plainly indicated by a film of oxide which forms on polished surfaces and shows a succession of colors dependent upon the temperature and consequent thickness of the oxide film. These colors merge into one another gradually, but those usually distinguished, with the temperatures and the class of tools for which they indicate a proper degree of hardness, are as follows:

Color	Approximate temperature.	Tools so tempered.
Pale yellow	220° C. (428° F.)	Engraving tools, fine drills, etc.
Straw	230° C. (446° F.)	Steel-cutting drills, milling cutters, etc.
Light brown	243° C. (469° F.)	Dies, taps, rock-drills, etc.
Brown	255° C. (491° F.)	Wood-cutting tools, etc.
Brown-purple	265° C. (509° F.)	Wood-cutting tools, etc.
Purple	277° C. (531° F.)	Cold chisels for steel and iron, etc.
Bright blue	288° C. (550° F.)	Axes, hacksaws, etc.
Pale blue	297° C. (567° F.)	Screwdrivers, needles, etc.
Dark blue	316° C. (601° F.)	Wood-saws, springs, etc.

122. Annealing Steels. Annealing has for its purpose (1) the relieving of any internal strains originating during cooling or caused by working, (2) the restoration of the grain of the steel to the minute size which is so desirable, and (3) the softening of the steel after hardening. The heating must be done very carefully and uniformly out of contact with the fuel, and the pieces must be supported so that they will not become distorted while hot. For any refinement of the grain the heating must be carried 25°–50° above the critical temperature Ac_3. Usually the steel is brought to a point just above the critical temperature and then cooled very slowly either by leaving it to cool down with the furnace or by removing it and letting it cool under a muffle. Small objects are enclosed in iron boxes or pots, and packed in charcoal or similar material to prevent decarburization.

123. Case-hardening Steels. Case-hardening is a form of cementation applied to low- or medium-carbon steels in order to impregnate them with carbon to a depth of perhaps one-fourth of an inch or less, thus securing a high-carbon case which may subsequently be hardened by quenching. The advantage gained by this treatment is that a surface is produced which will withstand wear, abrasion, cutting, or indentation and at the same time the core is left soft and tough so that the shock resistance of the material is not impaired. Case-hardening is especially applicable to the construction of armor-plate, safes and vaults, the moving parts of machinery which are subjected to both shock and wear, such as crank shafts, pivots and axles, gears, etc., also for the bearings and knife-edges of weighing machinery, and for many other purposes in machine and implement construction. For many of the purposes above listed certain of the alloy steels which combine great hardness with great toughness are now often preferred.

The steel used for case-hardening usually is one containing from 0.1 to 0.2 per cent carbon originally, and the operation is usually applied to the finished casting, forging, or otherwise fabricated object, so that no machine work need be done on the hardened surface.

The general method of case-hardening consists in heating the steel in contact with carbonaceous matter such as potassium ferro-cyanide, charcoal, barium carbonate, bone dust, charred leather, etc. The usual temperature of heating is about 900° C. (1652° F.). A more rapid penetration of the carbon may be secured by the use of higher temperatures, but this practice is attended by the danger of the growth of coarse grains in the interior at the temperature of carbonation, resulting in loss of toughness and strength unless the steel is subsequently reheated to restore the grain size. A time of from two to twelve or more hours is required for the process, depending upon the temperature of the furnace and the class of carburizer used. Many special or alloy steels are often treated by a case-hardening process with very beneficial results. Nickel and chrome steels are especially valuable steels for case-hardening.

Occasionally it is the practice to secure the hardening of steel which has thus been surface carburized by quenching the steel as it comes from the furnace. A far better practice, however, is to allow it to cool, and then reheat and harden in the usual manner. This operation not only tends to remove any lack of toughness caused by coarse crystalline growth, but also causes a diffusion of the carbon inward, leaving a less distinct plane of weakness between the carburized shell and the unaltered core.

THE PROPERTIES AND USES OF STEELS

STRUCTURE AND CONSTITUTION

124. The Constituents of Steels. The normal constituents of steels and irons are generally considered to be *ferrite*, which is theoretically pure iron entirely free from carbon, *cementite*, which is the carbide of iron, FE_3C, and *graphite*, which is practically pure amorphous carbon. We must now recognize the existence of various modifications and solutions of these constituents whose existence is dependent upon the amount of carbon present and the rate of cooling from solution. These modifications of the normal constituents can only be considered in connection with the behavior of iron carbon solutions in cooling.

125. Compounds and Solid Solutions. Eutectics. Steels are metallic alloys consisting of an intimate mixture or solution of metals with non-metals, forming when melted a homogeneous fluid. This molten steel is composed of carbide of iron dissolved in liquid iron and as the solution cools and freezes the carbide and iron form a "solid solution."

A solid solution differs from a mixture in that there is no separation of either of the pure constituents in freezing, and even the microscope is unable to distinguish the different components. The solution appears to be a simple homogeneous body. A solid solution differs from a chemical compound principally because it may contain widely varying amounts of each component while a compound must always hold certain definite relative amounts of each component, and in some multiple of their atomic weights.

There is a limit, however, to the amount of carbon which can be carried with iron out of the liquid state in solid solution. This limit is reached when the iron contains about 1.7 per cent of carbon. No solid solution of carbon and iron will form containing more than about 1.7 per cent of carbon, and any additional carbon must remain out of solution either as cementite or as graphite. All irons, therefore, which contain more than the amount of carbon which can be held in solution should not be classed as steels but as cast iron or intermediate products between steel and cast iron.

Eutectics. When a solution of two dissimilar constituents is cooled, the freezing-point of one or the other of the constituents will normally be reached before the freezing-point of the solution as a whole is reached. When selective freezing takes place with separation of one or the other of two constituents, one of the constituents will continue to separate until the liquid remaining has reached a definite concentration when the two constituents will separate simultaneously at constant temperature. This particular concentration is known as the eutectic. It is evident that the concentration of the original liquid may be of eutectic concentration, in which case this liquid of definite concentration will solidify as a whole at definite temperature. When the original solution is a solid solution the eutectic is spoken of as a eutectoid. The eutectoid of iron (ferrite) and iron carbide (cementite) contains 0.85 per cent of carbon and is known as *pearlite.*

Phenomena of Slow Cooling of Iron-carbon Alloys

126. Freezing of Iron-carbon Alloys. If a molten alloy or solution of carbide of iron (cementite) in iron contains an excess of the carbide over the eutectic ratio, carbide of iron will crystallize out in cooling until the remaining solution is of eutectic composition, when it will all crystallize out together. Such an alloy is called a "hyper-eutectic" alloy. On the other hand, if an excess of iron is present "austenite," the solid solution of iron and carbide of iron which is normal at all temperatures above about 880° C. (1616° F.), will crystallize out and continue to do so until the remaining solution is of eutectic composition. Such an alloy is called a "hypo-eutectic" alloy. The eutectic formed is a saturated solution of "austenite" and cementite, the composition of the eutectic being definitely fixed at 95.7 per cent iron and 4.3 per cent carbon.

The freezing of iron-carbon alloys is depicted graphically by the diagram of Fig. 31. The significance of the diagram may be explained as follows:

With any hypo-eutectic alloy the temperature at which the austenite

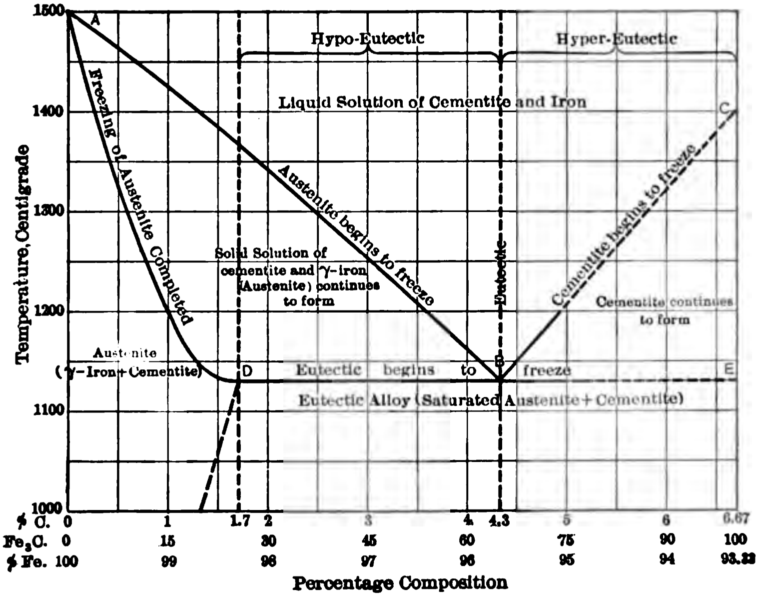


FIG. 31. — The Freezing of Iron-carbon Alloys.

will begin to freeze is indicated by the line *AB*, and the temperature at which the freezing of austenite is completed is indicated by the line *AD*. Thus if an alloy contains 1 per cent carbon, its austenite will begin to freeze at about 1430° C. (2606° F.) and it will have become wholly solid at about 1200° C. (2192° F.). Any alloy of carbon and iron will behave similarly so long as the carbon content does not exceed 1.7 per cent. When the carbon content lies between 1.7 per cent and 4.3 per cent a selective precipitation of austenite occurs until the liquid solution becomes so impoverished in iron that its composition approaches the eutectic ratio, and final solidification takes place when the eutectic is reached. Thus an alloy containing 3 per cent carbon will begin to precipitate austenite at a temperature of about 1250° C. (2282° F.) and all of the austenite will have crystallized out before a temperature of about 1135° C. (2075° F.), is reached. As the remaining solution becomes impoverished in iron and continues to cool, its position moves along the line *AB* of the diagram until the eutectic composition is reached at *B*, when further cooling causes it to crystallize out of solution.

With any hyper-eutectic alloy (more than 4.3 per cent carbon) cooling causes cementite to begin to crystallize out as soon as the line *CB*, Fig. 31, is reached. The liquid solution thus becomes progressively impoverished in cementite, and with continued cooling its position moves along the line *CB* until the eutectic is formed upon cooling below point *B*.

127. Changes in Cooling below the Freezing-point. When the solid solutions of carbon and iron are further cooled they are found not to be stable, but decompose at various temperatures, dependent upon the carbon content. Austenite decomposes into cementite and ferrite, and as the cooling continues the ferrite successively assumes two allotropic forms at temperatures below that temperature at which the γ form of ferrite exists. These allotropic forms of ferrite are β-iron and α-iron.

The molecular change in iron passing from the γ form to the β form, and subsequently from the β form to the α form, is attended by the evolution of a certain amount of heat which causes a "retardation" in the rate of cooling. Furthermore, a third retardation occurs in iron-carbon alloys when the temperature is reached at which the residual solution of the original solid solution (after precipitation of ferrite or cementite) finally decomposes into its constituents, ferrite and cementite.

These three temperatures at which retardations occur in cooling are called the "critical points" in cooling. They are usually designated as A_1, A_2, and A_3, respectively, in order of increasing temperature. The range of temperature included between points A_1 and A_3 is known as the "critical range" of temperatures.

Exactly the reverse phenomena occur in heating steel through this same range, a sudden absorption of heat and a consequent falling off in the rate of heating being observed at each critical point. The critical points on heating are slightly higher than the corresponding critical points in cooling, owing to a lag or hysteresis effect, the physical change not occurring immediately when the temperature which should produce it is reached. The critical points in heating are usually distinguished from the corresponding points in cooling by designating the former Ac_1, Ac_2, Ac_3 and the latter Ar_1, Ar_2, Ar_3.* As the amount of carbon in the steel increases, the Ar_3 and Ar_2 points approach each other until they coincide, when the carbon content is about 0.35 per cent, and the critical point is then designated $Ar_{3,2}$. Further increase in carbon to about 0.85 per cent causes the $Ar_{3,2}$ point to coincide with Ar_1 and the resultant single critical point is designated $Ar_{3,2,1}$.

The approximate position of the critical points in cooling various steels is indicated by the time-temperature curves, or cooling curves, of Fig. 32.

By observing the

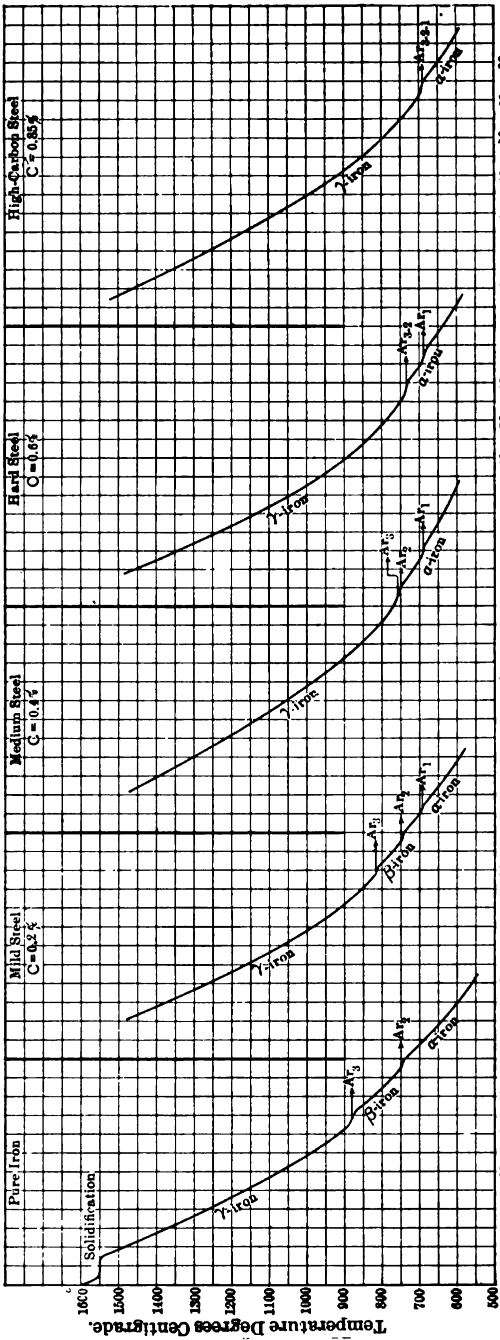


FIG. 32. — Critical Temperatures, Cooling Curves for Various Steels.

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* r stands for the French *refroidissement*, meaning cooling, and c for the French *chauffage*, heating.

position of the critical points in cooling for a considerable number of steels whose carbon content varies over a wide range, the complete equilibrium diagram of iron-carbon solid solutions shown in Fig. 33 may be derived. The significance of this diagram may be explained as follows:

Consider first a hypo-eutectoid alloy containing 0.2 per cent carbon. In cooling from above 900° C. (1652° F.) the first critical point, Ar_3, is encountered at a temperature of about 845° C. (1553° F.). (Intersection with line *FG*, Fig. 33.) Ferrite now begins to be precipitated from the austenite, being transformed from the γ form to the β form. β iron continues to form until the second critical temperature, Ar_2, is reached at about 760° C. (1400° F.), when the β iron begins to assume the α modification. As the remaining solid solution becomes more and more impoverished in iron through precipitation of ferrite its position moves along the line *FGM* until, when the critical point Ar_1 is reached, at a temperature of about 690° C. (1274° F.) the austenite is of eutectoid composition (0.85 per cent carbon) and on further cooling becomes pearlite.

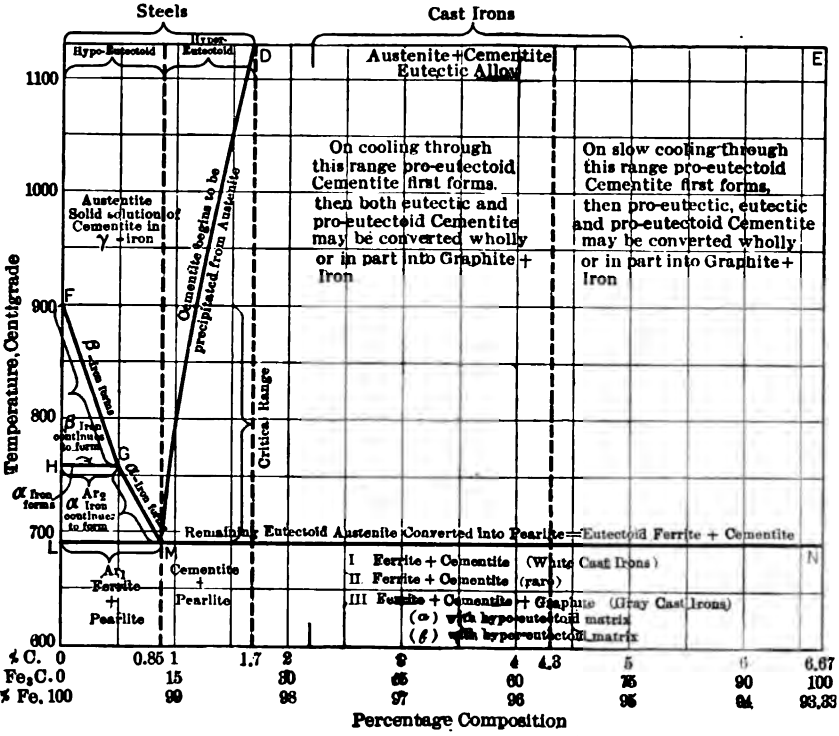

FIG. 33. — Solid Solution Equilibrium Diagram.

If the hypo-eutectoid alloy were one containing 0.6 per cent carbon, its ferrite would begin to be precipitated as iron when the critical point $Ar_{3,2}$ is reached, at a temperature of about 745° C. (1373° F.). (Intersection with line *GM*, Fig. 33.) The selective precipitation of ferrite in the α form will continue with further cooling until the remaining solid solution is again of eutectoid composition, when it will be converted into pearlite at the critical point Ar_1.

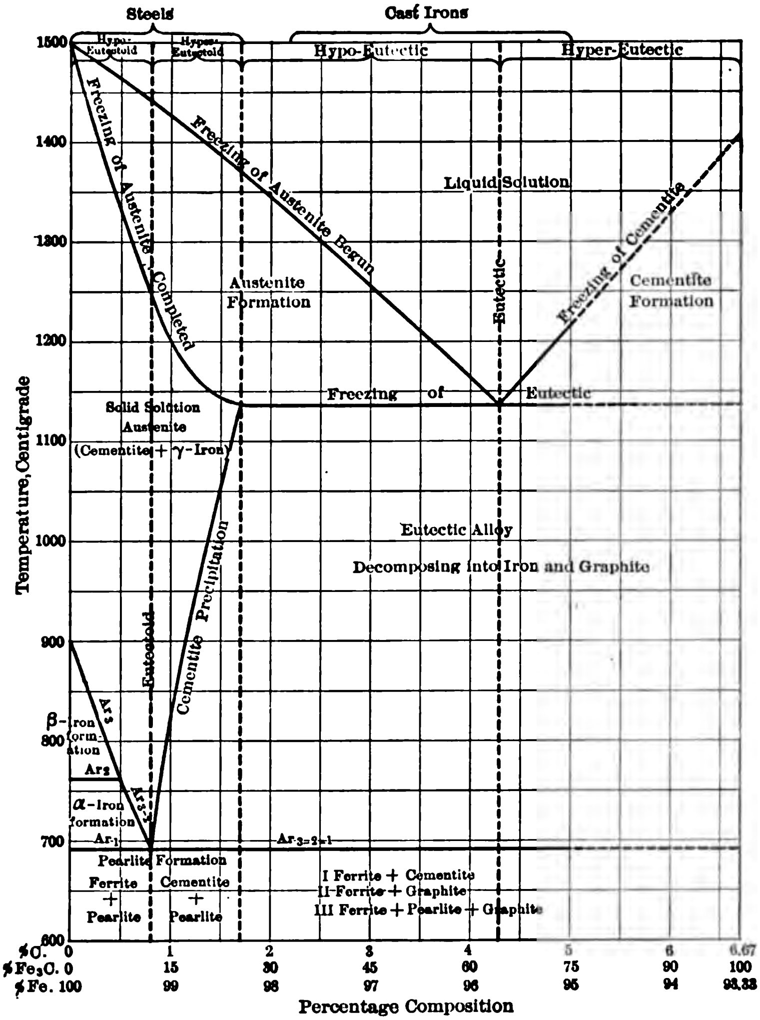

FIG. 34. — Equilibrium Diagram for Iron-carbon Alloys.

Now consider a hyper-eutectoid alloy containing 1.2 per cent carbon.

In cooling from 1000° C. (1832° F.), for instance, the first transformation will occur when the line *DM*, Fig. 33, is encountered at a temperature of about 900° C. (1652° F.). Cementite now begins to be precipitated from the solid solution and continues to crystallize out until the remaining austenite has reached the eutectoid composition, when it again becomes transformed into pearlite.

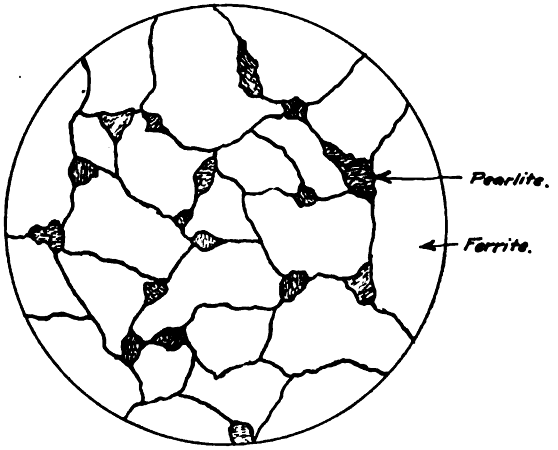

FIG. 35. — Micro-structure of Low-carbon Steel. Carbon = 0.08%. (Arnold.)

Lastly, considering the changes which occur upon cooling the eutectic alloy of cementite and austenite below its freezing-point (about 1135° C. 2075° F.), we find that pro-eutectoid cementite (cementite whose formation immediately precedes the formation of the eutectoid) first forms, followed by the decomposition of a part or all of the cementite into ferrite and graphite. This latter conversion process is greatly affected by the presence of the various impurities such as silicon, manganese, phosphorus, and sulphur, which are always present in cast irons, and the precipitation of graphite in particular is especially affected by the rate of cooling. According to the relative potency of these various factors the ultimate constitution of the iron may be that of white cast iron or gray cast iron, or even a combination of the two.

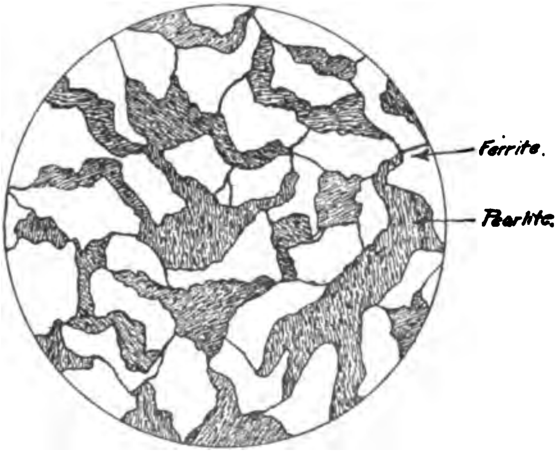

FIG. 36. — Micro-structure of Medium Steel. Carbon = 0.38%. (Arnold.)

The complete equilibrium diagram for iron-carbon alloys, Fig. 34, is simply a combination of Figs. 31 and 33. The complete history of the cooling of any iron or steel may be followed through the equilibrium diagram of Fig. 34, just as has been done separately for the ranges of temperatures above and below the freezing-point.

The structure of slowly cooled steel as revealed under the microscope will, in the case of a low-carbon steel, be a mass of ferrite with isolated particles of pearlite occurring at the junction of the grains of ferrite (Fig. 35). For a medium-carbon steel the proportion of pearlite is increased and the ferrite correspondingly decreased (Fig. 36). The structure of eutectoid steel is that of a mass of pearlite grains. Lastly, in hyper-eutectoid steel the excess cementite over the amount required to form pearlite will be rejected to the boundaries of the pearlite grains, the appearance of the structure being as shown in Fig. 37.

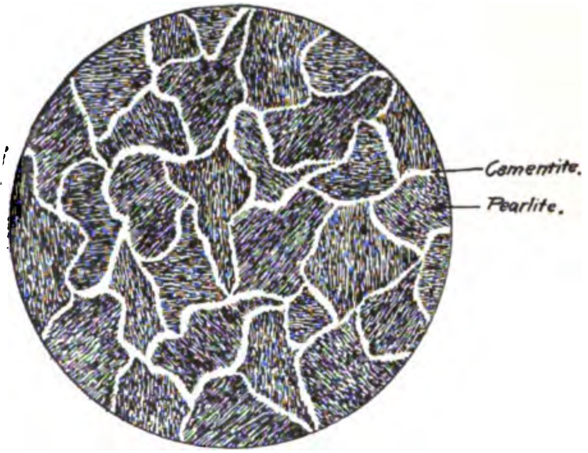

Fig. 37. — Micro-structure of High-carbon Steel. Carbon = 1.4%.

Phenomena of Rapid Cooling Followed by Various Reheating Treatments

128. Effect of Various Heat Treatments upon the Structure and Constitution of Steels. The practice of applying various heat treatments to steels has been discussed above in Arts. 119 to 123 inclusive, but the actual changes produced in constitution and structure were not considered at that point.

Hardening. When carbon steels are heated above the transformation range (above the line *FGMD*, Fig. 33) the aggregate of ferrite and cementite normal to slowly cooled steels is converted into austenite, and upon subsequent rapid cooling the normal transformation of austenite back to ferrite and cementite is prevented, at least in part, because of lack of time afforded at the transformation temperatures. In the ordinary practice of hardening steels the partial transformation of austenite back to ferrite and cementite gives rise to certain transitory forms which are known as "martensite," "troostite," and "sorbite." These various constituents of hardened steels are defined as follows by the Committee on Nomenclature of the Microscopical Substances and Structures of Steel and Cast Iron of the International Association for Testing Materials:

Austenite. "The iron-carbon solid solution as it exists above the transformation range or as preserved with but moderate transformation at lower temperatures, e.g., by rapid cooling, or by the presence of retarding elements (Mn, Ni, etc.), as in 12 per cent manganese steel and 25 per cent nickel steel."

Martensite. "The early stage in the transformation of austenite, characterized by needle structure and great hardness, as in hardened high-carbon steel."

Troostite. "Probably aggregate. In the transformation of austenite, the stage following martensite and preceding sorbite."

Sorbite. "In the transformation of austenite the stage following troostite (and osmondite if this stage is recognized), and preceding pearlite."

Austenite has already been declared to be a solid solution of carbon, or more probably, Fe_3C and γ iron. It is stable above the line *LMN*, Fig. 33, and may have any carbon content up to the saturation point indicated by line *MD*. Austenite is relatively soft, not as hard as martensite. In hardened high-carbon steel it may form a ground mass which is interspersed with martensite.

Martensite is usually considered to be a solid solution of carbide of iron, Fe_3C, in iron, the latter being partly in the α form and partly in the β form. It is not in equilibrium in any part of the diagram, but represents a metastable condition in which the metal is caught during rapid cooling. It is very hard and is the chief constituent of hardened high-carbon steels and of medium nickel and manganese steels. In less fully transformed steels it is associated with austenite, and in more fully transformed steels with troostite and even with ferrite or cementite.

Troostite is an uncoagulated conglomerate. The degree of completeness of the transformation represented by it probably varies widely, as does its carbon content. It arises on cooling through the transformation range at an intermediate rate, or on reheating hardened high-carbon steel to about 400° C. (752° F.). It may occur associated with martensite, and is intermediate in hardness between that of the martensitic and the pearlitic state corresponding to its carbon content. Tempering remarkably increases its ductility and lowers its hardness and elastic limit.

Sorbite is believed to be "essentially an uncoagulated conglomerate of irresoluble pearlite with ferrite in hypo-eutectoid steels and with cementite in hyper-eutectoid steels, respectively, but it also contains some incompletely transformed matter." It arises in reheating hardened steels above 400° C. (752° F.), but not to 700° C. (1292° F.), at which temperature it coagulates into granular pearlite. It also arises in quenching small pieces of steel in a medium which cools the metal slowly, and in water quenching from a temperature near the lower end of the transformation range. It is softer than troostite, and is habitually associated with pearlite. It is slightly less ductile than pearlitic steel of the same carbon content, but greatly excels the latter in strength and elastic limit. In fact a sorbitic steel possessing the same degree of ductility as a higher carbon pearlitic steel will greatly excel the latter in strength and elastic limit.

Pearlite is a definite conglomerate of ferrite and cementite containing about six parts of the former to one of the latter. When pure, its carbon content is about 0.85 per cent (often stated to be 0.9 per cent). It results from the completion of the transformation of eutectoid austenite accomplished by the slow cooling of any iron-carbon alloy below the transformation range, or held at temperatures within or slightly below that range long enough to allow the ferrite and cementite to coagulate. It is called "granular" pearlite when the cementite forms fine globules in a matrix of ferrite, and "laminated" or "lamellar" pearlite when the ferrite and cementite exist as alternate parallel lamellæ.

The fact must not be lost sight of that the hardness obtained by any treatment of steel is not alone dependent upon the heat treatment and consequent prevailing character of the constituents, e.g., martensitic, sorbitic, etc., but that the character of each of these constituents is dependent upon its carbon content, and therefore the hardness obtainable by a given hardening treatment is directly proportional to the amount of carbon in the steel used.

Tempering. The necessity for tempering hardened steels, and the explanation of the fact that hardened steels can be tempered by reheating to only moderate degrees far below the critical range of temperatures, has been explained above. There remain to be explained, however, the changes in constitution and structure which take place when hardened steels are tempered.

It will first be necessary to recall that hardened steels may theoretically be either austenitic, martensitic, troostitic, troosto-martensitic, or troosto-sorbitic. Sorbitic and pearlite steels are not really hardened and therefore cannot be tempered. The tempering of each of the other classes of steel will be separately considered.

Austenitic steel is not produced by ordinary commercial methods of hardening except possibly in the case of certain alloy steels like manganese steel. Under most carefully controlled conditions, a carbon steel which is partially austenitic may, however, be derived. Austenite undergoes transformation to martensite as soon as heating is begun, and martensite alone exists when a temperature of 200° C. (392° F.) is reached. The martensite begins to be transformed to troostite at 200° C. (392° F.), the latter alone remaining when a temperature of 400° C. (752° F.) is reached. Further heating above 400° C. (752° F.) causes the gradual conversion of troostite into sorbite, and the latter alone exists above 600° C. (1112° F.). If the heating were continued past the critical temperature austenite alone could exist.

Austenitic steel, on being heated, apparently begins to be transformed from the austenitic to the troostitic condition directly, the intermediate martensitic form not being observed. Notwithstanding the fact that the martensitic form is not observed, it is not impossible that it may have been formed and still have escaped detection simply because the succeeding transformation of martensite to troostite follows very quickly.

Martensite is a common constituent of commercially hardened steels, being far less unstable than austenite. Conversion of martensite into troostite begins almost immediately when heating is begun and no martensite exists if heating is carried beyond 400° C. (752° F.). Further heating causes conversion of troostite into sorbite, and sorbite alone exists between 600° C. (1112° F.) and the critical temperature.

Troostite is a still more common constituent of commercially hardened steels because it is decidedly more stable than austenite or even martensite. When troostitic steel is tempered, no change is effected unless heating be carried beyond 400° C. (752° F.), when the changes above noted for other steels again take place. If wholly troostitic steels were encountered in practice no tempering would be required, but since some martensite is usually present in even the most distinctly troostitic steel, tempering is required. The change which takes place is the gradual transformation of the martensite to troostite, no martensite being present above 400° C. (752° F.).

Troosto-sorbitic steels are a rare possibility among commercially hardened steels. The degree of hardening is so slight and the constituents so stable that tempering does not produce any effect unless carried above 400° C. (752° F.), when the troostite is gradually converted into sorbite.

The extreme range of temperature used in commercial tempering is, from about 200° C. (392° F.) to slightly above 300° C. (572° F.). It is evident, therefore, that the only constituents encountered in tempered eutectoid steels are troostite and martensite. In this statement austenitic steels are not taken into account because they are not encountered in practice, and troostitic and troosto-sorbitic steels might also be left out of consideration because they require no tempering and are not affected by heating to the ordinary temperatures.

Two considerations which affect the practice of tempering steels follow. First, the transformation of one constituent to the succeeding form is not solely dependent upon the temperature attained, but is also dependent upon the relative rapidity or slowness with which the temperature is reached, and upon the time allowed at this temperature. Slow heating, or holding at a given temperature for a measurable interval, will produce a greater degree of tempering than would otherwise be effected at a given temperature. Second, when, as is often the case in practice, the reheating of the hardened steel is done in such a manner that, if not arrested quickly, the temperature would continue to rise after reaching the desired tempering heat, it is necessary to cool the metal quickly by immersion in some quenching medium. This explains the reason for the common tempering practice of quenching from a rising temperature. If the temperature is not rising after the desired tempering effect is reached it is immaterial whether quenching follows or not. As a matter of convenience quenching almost invariably follows reheating in the commercial heat treatment of steels.

Annealing. The statement is made above that annealing is done with any or all of the following purposes in view: (1) The relieving of any internal strains originating during cooling or caused by working, (2) the restoration of the grain of the steel to a minute size, and (3) the softening of steel after hardening. The accomplishment of each of these objects will be separately considered.

Cooling strains originate owing to the circumstance that all portions of a piece of steel cannot be cooled evenly. All carbon steels contract rapidly while cooling and, since cooling proceeds from the exterior inward, the contraction of the exterior of a piece of steel tends to compress the interior and cause it to flow. The action is aggravated by the fact that after the exterior has passed that critical range in cooling, the interior stops contraction or expands while passing the critical points. The effect is most marked when the section is large, or where an abrupt change from a large to a small section occurs. Under ordinary circumstances cooling strains are not excessive except when steel has been rapidly quenched from a high temperature.

Internal strains are introduced by cold working owing to the actual distortion of the crystalline elements (pearlite, ferrite, and cementite) in the direction of application of pressure, and may result in marked decrease in ductility and even induce great brittleness. An extreme example of this effect is exhibited by cold-drawn wire, which at various stages in the drawing operation must be annealed in order to make further drawing possible.

The effect of annealing in relieving internal strains is due to the increase in molecular mobility afforded by the higher temperature. The annealing temperature recommended for this purpose by the American Society for Testing Materials is about 775° C. (1427° F.), followed by slow cooling, the rate of cooling being dependent upon the thickness of the piece. Thick pieces may require very long exposure to the annealing temperature followed by very slow cooling.

The coarse crystallization which results from the overheating of steel (above about 1100° C. (2012° F.), for medium-carbon steel), not followed by hot working, constitutes a great impairment of the physical qualities of all classes of carbon steels. Low-carbon steels are principally injured in that their ductility is impaired, while medium- and high-carbon steels lose both ductility and strength.

Coarse crystallization can only be corrected by heating to above the critical range of the particular steel in hand, followed by slow cooling. The effect is the obliteration of existing crystallization and the formation of a new finely crystalline structure. Heating must not be carried much above the critical range, however, for the new crystals formed in passing this range increase in size rapidly as the temperature increases. Hypo-eutectoid steels must be heated just above the line *FGM*, Fig. 33, and hyper-eutectoid steels just above the line *LMN*. The American Society for Testing Materials recommends the following range of annealing temperatures for steels of the carbon content stated:

Range of carbon content, Per cent.	Range of annealing temperature, Degrees C.
Less than 0.12	875 to 925° C. (1607 to 1697° F.)
0.12 to 0.29	840 to 870° C. (1544 to 1598° F.)
0.30 to 0.49	815 to 840° C. (1499 to 1544° F.)
0.50 to 1.00	790 to 815° C. (1454 to 1499° F.)

One of the forms of coarse crystallization which is not caused by overheating, and which is peculiar to very low-carbon steel is what is called *Stead's brittleness*. When very low-carbon steel is exposed for very long periods to temperatures ranging from 650° C. (1202° F.) up to but not exceeding 750° C. (1382° F.), extremely large crystals are formed which affect ductility just as overheating does. The conditions which render Stead's brittleness possible are so seldom met with in practice that the phenomenon is not often encountered. The remedy is exactly the same as if the coarse crystallization had been due to overheating, i.e., annealing by slow cooling from above Ac_3.

Annealing for the purpose of rendering a hardened steel less hard or less brittle is nothing more than tempering carried to the extreme by very slow cooling following moderate heating. The changes which take place will be understood from the above discussion of tempering.

The Physical Properties of Steels

129. Grades of Steel and General Properties. The following grades or classes of steels are among those most commonly recognized, their approximate tensile properties being as indicated:

Class by uses.	Class by manufacture, etc.	Per cent C.	Elas. lim. Lbs. per sq. in.	Ten. str. Lbs. per sq. in.	Per cent elong. in 8".
Boiler rivet	Dead soft O. H.	0.08–0.15	25,000	50,000	30
Structural rivet	Soft O. H.	0.15–0.22	30,000	55,000	30
Boiler plate	Soft Bess. or O. H.	0.08–0.10	30,000	60,000	25
Structural steel	Medium O. H.	0.18–0.30	35,000	65,000	25
Machinery steel	Hard O. H.	0.35–0.60	40,000	75,000	20
Rail steel	Hard Bess. or O.H.	0.35–0.55	40,000	75,000	15
Spring steel	High Carbon O.H.	1.00–1.50	60,000	125,000	10
Tool steel	High Carbon O.H. or crucible.	0.90–1.50	80,000	150,000	5

The modulus of elasticity of all grades is about 30,000,000 pounds per square inch.

130. Tensile and Compressive Strength in General. The tensile strength of steel is quite closely allied with the compressive strength, the properties revealed under one character of stress being practically identical with those revealed under the opposite character of stress. It is not necessary, therefore, to consider tensile strength and compressive strength separately, except to a slight extent. One fact which must not be overlooked in this connection is that soft or medium steel is often subjected to compressive loading under such circumstances that the stress induced does not remain purely compressive, but becomes a combination of compressive stress with bending stresses. The behavior of the material in this event is manifestly not that which is characteristic of steel in compression. When, for instance, compressive load is applied to a steel test specimen whose length is more than three or four times its diameter, or to a steel column whose length bears a large ratio to its least radius of gyration, complete failure occurs under a load which has induced an average compressive stress only slightly in excess of the yield point. Flow of the ductile metal at the yield point has caused eccentricity of stress, and failure ensues almost immediately owing to lateral flexure and the concentration of stress in the extreme fiber on one side of the section. For all practical purposes, therefore, the column strength of steel is identical with the yield point.

The principal factors influencing the strength, ductility, and elastic properties of steels are: (1) the per cent of carbon present, (2) the heat-treatment and the character and extent of the mechanical working to which it has been subjected, and (3) the content of silicon, manganese, sulphur, phosphorus, and other alloying elements. The factors are not necessarily independent, and their effects are usually combined. The nature and extent of the effect of heat-treatment, working, and the presence of alloying elements are inevitably dependent upon the amount of carbon present; the effects of heat-treatments and working are dependent upon the presence of alloying elements, etc.

131. Behavior of Steel under Stress in General. The behavior of steel under stress is best studied with the aid of the *stress-strain diagram.* Curve No. 1 of Fig. 38 presents a typical stress-strain diagram for a mild steel and Curve No. 2 shows the portion of Curve No. 1 between *O* and *B* to an enlarged horizontal scale. The *elastic limit* of the material (*A*, Curve No. 2) cannot usually be detected on a stress-strain diagram drawn to such a scale as to record the complete history of a test. Its position must be determined by observing the point of initial set in making a test. In the case of steel the elastic limit and proportional limit are usually considered to be identical. The *yield point B* is easily detected both in making a test (by the drop of the weighing lever of the testing machine), and from the stress-strain diagram, a more or less sharp break appearing in the curve when the yield point is reached. The *ultimate strength* is represented by the maximum ordinate to the stress-strain curve at *C*.

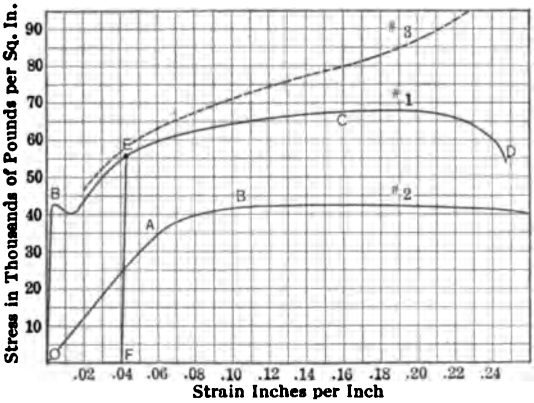

FIG. 38. — Stress-strain Curve for Mild Steel.

The distribution of elongation of a steel specimen in tension is illustrated by Fig. 39. If, uninfluenced by any local cause, a bar of homogeneous steel subjected to axial tension should fail at the center of the distance between the points of application of the load, because the flow of the metal will there be least impeded. The maximum ordinate to the curve of Fig. 39 represents the point where "necking down" occurred, since the point of maximum reduction in area must necessarily coincide with the point of maximum elongation. All steels except high-carbon steels exhibit the phenomenon of necking down, the action being most pronounced in the case of medium-carbon steels. The fact that steel test specimens are reduced in cross-section as they are elongated under stress, and finally neck down, accounts for the fact that the breaking load, according to the stress-strain diagram, is below the ultimate strength. If the stress were at all loads computed upon the basis of the actual section then existing, instead of being computed (as it always is) upon the basis of the original section, the stress-strain curve would follow such a course as is indicated by the dotted line curve No. 3 of Fig. 38.

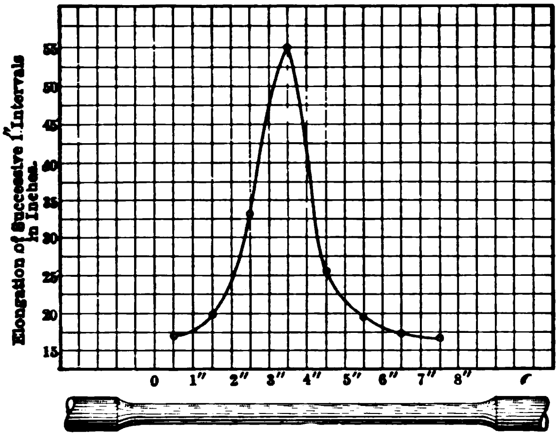

Fig. 39. — Distribution of Elongation.

The modulus of elasticity can be determined from the slope of the first portion of the stress-strain diagram, but is usually computed from the observed values of stress and strain. The modulus of elasticity is unaffected by the factors which influence other properties of steels and will, as above stated, be found in the neighborhood of 29,000,000 to 30,000,000 pounds per square inch for practically any class of carbon steel.

The tensile properties of various carbon steels called for in the standard specifications of the American Society for Testing Materials are summarized in the following table:

TENSILE PROPERTIES OF VARIOUS STEELS

Character and use of steel.		Tensile strength. Lbs. per sq. in.	Yield point. Lbs. per sq. in.	Elongation. Min. in 8 ins. Per cent.	Elongation. Min. in 2 ins. Per cent.	Reduction of area. Min Per cent.
Structural steel for bridges	Structural	55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$	22	
	Rivet	46-56000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for buildings	Structural	55-65000	0.5 (u.t.s.)	$\frac{1400000}{\text{u.t.s.}}$	22	
	Rivet	46-56000	0.5 (u.t.s.)	$\frac{1400000}{\text{u.t.s.}}$		
Structural steel for locomotives		55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for cars	Structural	50-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Flange plates	48-58000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for ships	Structural	58-68000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Rivet	55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Locomotive forgings untreated	Max. thickness 8″	75000	0.5 (u.t.s.)	....	$\frac{1600000}{\text{u.t.s.}}$	$\frac{2200000}{\text{u.t.s.}}$
	Thickness 8″-12″	75000	0.5 (u.t.s.)	....	$\frac{1500000}{\text{u.t.s.}}$	$\frac{2000000}{\text{u.t.s}}$
Locomotive forgings annealed	Max. thickness 8″	80000	0.5 (u.t.s.)	....	$\frac{1800000}{\text{u.t.s.}}$	$\frac{2800000}{\text{u t s}}$
	Thickness 8″-12″	80000	0.5 (u.t.s.)	....	$\frac{1725000}{\text{u.t.s.}}$	$\frac{2640000}{\text{u t s}}$
	Thickness 12″-20″	80000	0.5 (u.t.s.)	....	$\frac{1650000}{\text{u.t.s.}}$	$\frac{2400000}{\text{u t.s}}$
Cold-rolled steel axles		70000	60000 †	....	18	35
Steel castings	Hard	80000	36000	....	15	20
	Medium	70000	31500	....	18	25
	Soft	60000	27000	....	22	30
Boiler and firebox steel	Flange	55-65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Firebox	52-62000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Boiler rivet steel		45-55000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Billet Steel Concrete Reinforcing Bars — Plain Bars	Structural grade	55-70000	33000	$\frac{1400000}{\text{u.t.s.}}$		
	Intermediate grade	70-80000	40000	$\frac{1300000}{\text{u.t.s.}}$		
	Hard grade	80000	50000	$\frac{1200000}{\text{u.t.s.}}$		
Billet Steel Concrete Reinforcing Bars — Deformed Bars	Structural grade	55-70000	33000	$\frac{1250000}{\text{u.t.s.}}$		
	Intermediate grade	70-85000	40000	$\frac{1125000}{\text{u.t.s.}}$		
	Hard grade	80000	50000	$\frac{1000000}{\text{u.t.s.}}$		
Cold twisted bars		....	55000	5		
Concrete reinforcing bars from rerolled steel rails	Plain bars	80000	50000	$\frac{1200000}{\text{u.t.s.}}$		
	Deformed bars	80000	50000	$\frac{1200000}{\text{u.t.s.}}$		

u.t.s. stands for "ultimate tensile strength."

† Elastic limit, not yield point.

132. Effect of Carbon upon Physical Properties. The distinctive properties of the different grades of ordinary steels (i.e., not special alloy steels) are due to variations in carbon content more than to any other single factor. Carbon always acts as a hardener and strengthener, but at the same time reduces the ductility.

The effect of carbon upon the tensile properties of steels is shown by the following table.

RESULTS OF TESTS MADE AT THE WATERTOWN ARSENAL ON OPEN-HEARTH STEELS

Per cent carbon.	Yield point, pounds per square inch.	Ultimate tensile strength, pounds per square inch.
0.09	30,000	52,500
0.20	39,500	68,400
0.31	46,500	80,600
0.37	50,000	85,200
0.57	55,000	117,400
0.81	70,000	149,600
0.97	79,000	152,600

Many formulas have been suggested for the strength of carbon steels in terms of carbon, phosphorus, sulphur, manganese, etc., but none of them are continuous functions for any great range.

The marked effect of gauged length upon percentage elongation is shown by the series of curves plotted in Fig. 40, which are based upon a series of tests of open-hearth steel made by Mills. These tests were made upon 1-inch round bars 8 feet long, gauge points having been marked at 1-inch intervals along the entire length of each specimen. Each of the gauged lengths over which measurements were taken after fracture included the fracture and necked-down portion at the center, or within ½ inch of the center.

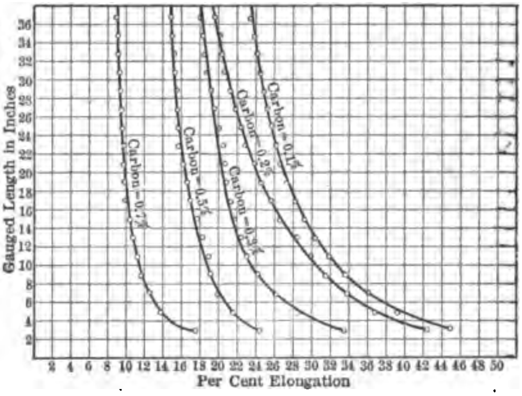

FIG. 40.

133. Effect of Heat Treatment and Mechanical Working. The effect of hardening, tempering, and annealing of steels upon structure, hardness, and brittleness, has been noted above in Arts. 119 to 128. The effect of the same treatment upon the strength and ductility may be summarized as follows:

Annealing at 350° C. (662° F.) has little effect upon the strength of low- and medium-carbon steels, but increases the strength of high-carbon steels slightly; the ductility of all steels is increased slightly.

Annealing at 750° C. (1382° F.) has little effect upon the strength of low- and medium-carbon steels, but decreases the strength of high-carbon steels slightly; the ductility of all steels is increased considerably.

Annealing at 850° C. (1562° F.) has little effect upon the strength of any class of steel, but increases the ductility considerably, particularly the high-carbon steels.

Annealing at 1000° C. (1832° F.) has practically no effect upon the strength of low- or medium-carbon steels, but slightly increases the strength of high-carbon steels; the ductility of all steels is increased slightly, the low-carbon steels more particularly.

Water quenching at 750° C. (1382° F.) increases the strength of low-carbon steels greatly, medium-carbon steels slightly, and scarcely affects the strength of high-carbon steels; the ductility of low-carbon steels is reduced very greatly, medium-carbon steels slightly, and high-carbon steels are scarcely affected at all.

Reheating to 550° C. (1022° F.), after water quenching at 750° C. (1382° F.), restores the steel to practically its original strength in all cases; the ductility is in every case much greater than that obtained after quenching, but is only slightly greater than that obtained with the steel in its original condition.

Water quenching at 850° C. (1562° F.) increases the strength of low-carbon and medium-carbon steels greatly, but scarcely increases the strength of high-carbon steels because of the increased brittleness; the ductility is reduced enormously for the low- and medium-carbon steels and is practically zero for high-carbon steels.

Reheating to 550° C. (1022° F.), after water-quenching at 850° C. (1562° F.), largely nullifies the gain in strength of low- and medium-carbon steels caused by quenching, and enormously increases the strength of high-carbon steels by removing brittleness; the ductility is restored to practically its original value before quenching.

Oil quenching at 750° C. (1382° F.), followed by reheating to 550° C. (1022° F.), has little effect upon the strength of any class of steel, but increases the ductility of low- and medium-carbon steels slightly, and high-carbon steels considerably.

Oil quenching at 850° C. (1562° F.), followed by reheating to 550° C. (1022° F.), increases the strength of all except the very low-carbon steels remarkably; the ductility of any grade of steel is not materially affected.

The first effect of hot mechanical working is the benefit derived from the elimination of flaws, blow-holes, etc. The coarse crystalline structure of steel slowly cooled from a high temperature is also improved by working, since the crystals become broken up, mixed intimately, thus destroying the continuity of their cleavage planes, and increasing both their cohesive and their adhesive power.

The amount of reduction necessary in rolling or forging the finished section from the ingot is dependent on many variable factors. It is a fact recognized in the ordinary practice of steel mills, however, that the finished section should never be more than 10 per cent of the ingot section, and it is commonly not more than 2 or 3 per cent, often being much less than 1 per cent.

The temperature at which working is finished is a very important consideration, since, if this temperature is above a red heat, the crystals grow to a certain extent, thus diminishing strength and especially lowering the elastic limit of the steel. In the ordinary practice of rolling structural steel the finishing heat is above the red heat and the elastic limit is therefore comparatively low. If the working be continued until the metal is not above a dull red heat, large crystals cannot reform, and strength and especially the elastic limit are increased.

Cold working of steels, i.e., the mechanical distortion of the metal below the critical range of temperatures, cannot be practiced except with low- or medium-carbon steels. The effect of cold working upon the existing structure is to elongate the crystalline elements in the direction of working. Cold working does not improve the crystalline structure as does working above the critical range, and the primary effect of cold working upon physical properties is a marked decrease in ductility and increase in brittleness. One other effect which constitutes a great practical advantage in the case of steels used for certain purposes, is the very material extent to which the elastic limit of steel may be raised by cold working. This fact is taken advantage of in the manufacture of certain grades of hard wire and in the finishing of steel rods intended for particular purposes. The extent of the effect of cold working is directly dependent upon how far below the critical range working is continued, and is most marked when working is done at atmospheric temperatures.

134. Effect of Silicon, Sulphur, Phosphorus, and Manganese. The direct effect of silicon, in the ordinary proportions commonly encountered in steels (usually not over 0.2 per cent), upon strength and ductility is very slight. Whatever effect there may be is difficult to determine, because it is masked by the influence of other elements, like carbon and phosphorus, which cannot be made to be altogether constant factors. Increasing the silicon content intentionally to 0.3 or 0.4 per cent has the effect of raising the elastic limit and ultimate strength of the steel considerably, without reducing the ductility greatly. This is sometimes done in the production of steel castings.

Sulphur, within the limits common to ordinary steels (0.02 to 0.10 per cent) has no appreciable effect upon the strength or ductility of steels. It has, however, a very injurious effect upon the properties of the hot metal in lessening its malleability and weldability, thus causing difficulty in rolling called "red-shortness." If it were possible that the steel might contain an excess of sulphur over that which is neutralized by manganese, the effect would certainly be to reduce both strength and ductility. Specifications for structural steels commonly limit the sulphur content to a maximum of from 0.04 to 0.05 per cent.

Phosphorus is the most undesirable of all the elements commonly found in steels. Its effect upon the properties of steels is very capricious, but it is always detrimental to toughness or shock-resistance, and often detrimental to ductility under static load. Campbell states that the strength of steel under static load is increased by 1000 pounds per square inch for each 0.01 per cent of phosphorus so long as the total phosphorus does not exceed 0.12 per cent. Beyond this limit even static strength is diminished. High-phosphorus steels are apt to break under very slight stress if this stress is suddenly applied or if vibration is encountered, and this fact alone is sufficient to bar such steels from most uses in construction. Specifications commonly limit the phosphorus content of structural steels to a maximum of from 0.04 to 0.06 per cent.

Manganese is an element which is commonly comparatively high in most steels because of the prevalent practice of using either spiegeleisen or ferro-manganese as a recarburizer and deoxidizer in the Bessemer and open-hearth processes. The effect of manganese upon the properties of steel is a rather involved question, but it has a tendency to increase the strength provided a certain limit is not exceeded. If this limit is exceeded its effect in the direction of increasing brittleness causes a reversal of its effect upon strength. With less than 0.3 or 0.4 per cent manganese the steel is apt to be impregnated with oxides whose harmful effect outweighs any beneficial effect due to the manganese. Between 0.3 or 0.4 per cent and about 1.5 per cent manganese, the beneficial effect is dependent upon the amount of carbon present. With 0.1 per cent of carbon (according to Bradley Stoughton), the strength is increased about 100 pounds per square inch for each 0.01 per cent of manganese over 0.3 or 0.4 per cent; with 0.2 per cent carbon, the gain is about 165 pounds per square inch for each 0.01 per cent of manganese; and with 0.4 per cent of carbon the gain is about 280 pounds per square inch for each 0.01 per cent of manganese. In all cases the beneficial effect is somewhat more marked with acid than with basic steel. As the content of manganese rises above 1.5 or 2.0 per cent the metal becomes so brittle as to be worthless, but as the content of manganese is further increased a curious reversal takes place with about 6 or 7 per cent of manganese.

135. Shearing Strength. The shearing strength of steel is dependent upon about the same factors as the tensile and compressive strength. It is therefore to be expected that a more or less constant relation may be found between the shearing strength and the tensile strength. Experiments have amply demonstrated that such a relationship does exist, and have further shown that the value of the factor for most grades of steel is about 0.8, i.e., the shearing strength is about eight-tenths of the tensile strength.

The intensity of the shearing stress due to torsion on any section of a cylindrical shaft is not uniform, but varies directly as the distance from the axis of the shaft (considering that the section is circular), and the maximum intensity of shearing stress is therefore found at the circumference. The mathematical expression for the maximum shearing stress in the extreme fiber of circular shafts is:

$$s = \frac{2\,Pa}{\pi r^3},$$

(wherein Pa is the torque, r is the radius of the section, and s the shearing stress in the extreme fiber of the shaft), and the shearing modulus of elasticity is expressed by the equation

$$E_s = \frac{sl}{r\theta}$$

(wherein l is the distance between the planes of the external forces, and θ is the angle of torque or twist).

From the following table, which is a summary of a series of tests made by Mills, it will be noted that the shearing strength as determined by torsion tests appears higher than it does in the case of direct shear. This is due to the fact that the expression for s above is true only as long as the

STRENGTH OF STEEL IN TORSIONAL SHEAR

Class of steel.	Computed extreme fiber stress. Lbs. per sq. in.	Shearing mod. of elasticity. Lbs. per sq. in.
Mild Bessemer	64,200	11,320,000
Medium Bessemer	68,300	11,570,000
Hard Bessemer	74,000	11,700,000
Cold-rolled	79,900	11,950,000

material behaves elastically. When computed for the torque which produces rupture it may be called the "torsional modulus of rupture" and corresponds to the true value of the shearing strength of the material in about the same way as the modulus of rupture for cross-breaking corresponds to the actual extreme fiber stress.

Upton has shown that a definite relation exists between the shearing modulus of rupture and the direct shearing strength, the relation being that the true shearing strength of steel is approximately equal to three-fourths the value of the torsional modulus of rupture. This fact is of value, because torsion tests are much more easily made than are direct-shear tests. The modulus of elasticity for shear is about $\frac{2}{5}$ of the tensile modulus.

136. Transverse Strength, Flexure and Deflection. The transverse strength of steel is directly dependent upon the tensile and compressive properties of the metal, for failure in cross-bending must necessarily occur either through failure of the loaded side of a beam in compression or by failure of the opposite side in tension. Whether the former or the latter is the controlling factor is dependent upon the form of the beam and the location of the neutral axis. If the section is symmetrical the failure will usually occur on the tension side if the steel is not a ductile grade, and on the compression side if the steel is a ductile grade. Absolute rupture in cross-bending is not possible with any grade of mild or medium steel, since these steels may be bent 180 degrees flat without fracture. Some cast steels and most high-carbon steels may be actually ruptured.

The modulus of elasticity as obtained from bending tests is slightly lower than the values obtained from tensile or compression tests. The reason for this variation is the slight deflection due to the shear which introduces a small error into the usual formulæ for deflection from which the transverse modulus is usually calculated.

137. Hardness of Steels. The precise meaning of the term hardness as applied to metals is not altogether fixed. Hardness referring to machine cutting tools means the ability to hold an edge while cutting metal; with respect to steel rails and the tires of car wheels it means the resistance to dry rolling friction; applied to the tires of locomotive drivers the term involves dry rolling friction combined with slippage; applied to axles and bearings it means resistance to wear between lubricated surfaces; respecting the performance of gears it means not only frictional wear between lubricated surfaces, but also involves toughness; the hardness of the crushing faces of rock-grinding machinery is a measure of resistance to combined abrasion and shock; the hardness of machinery steel is a measure of the difficulty experienced in cutting or machining it.

Properly, the toughness and resiliency of steel are properties distinct from hardness, and resistance to wear is quite a different thing from resistance to cutting or indentation, but the term hardness is used meaning any or all of these things.

The *Brinell* method is based upon determining the resistance offered to indentation by a hardened sphere, the latter being subjected to a given pressure. Brinell expressed the hardness by the pressure in kilograms per square millimeter of spherical area of indentation.

The pressure used in testing steel is usually 3000 kilograms and the diameter of the ball is 10 mm.

If the Brinell number is multiplied by 500 to 520 a very close approximation of the tensile strength of the steel will be obtained. This relationship holds for all grades of carbon steel whether in the natural condition or heat treated.

The *Rockwell* method is similar to the Brinell. The depth is not measured from the surface of the work however. Two superimposed impressions are made, one with a load of 10 kilograms and the other with a load of 100 kilograms. The depth to which the major load drives the ball below that to which the minor load has previously driven it is the hardness number. This method is very useful for soft material and for sheet metal.

The cone test, first proposed by Ludwick, is the same in principle as the Brinell test, but a hardened steel cone of 90° angular opening is substituted for the steel sphere. The hardness numeral is computed on the basis of the pressure divided by the area of the conical indentation. The relation between the load and the hardness numeral thus obtained is not a constant or straight-line relation, but is a parabolic relation. The hardness scale obtained by the cone test is therefore not a uniform scale. The cone test fails on very hard steel because of the flattening of the point of the cone under the heavy pressure required.

The Shore scleroscope test is made by the use of a pointed hammer which is allowed to fall through a guiding glass tube upon the metal being tested. The hardness is expressed by the height of rebound of the hammer after falling from a specified height. The hammer of the instrument becomes slightly changed in form after a certain number of tests and must then be recalibrated. The indications of the instrument must certainly be dependent in some measure upon the resiliency of the material tested as well as that of the hammer itself, but the extent of the permanent deformation of the metal is also a factor. For ordinary steels the Brinell number is approximately the Scleroscope number multiplied by 5¾ to 6.

The Bauer drill test is made by the use of a special drill driven at constant speed with a fixed pressure of the drill upon the specimen of steel. The hardness is measured by the depth of the hole drilled with a given number of revolutions, the pressure remaining constant. This test is of course simply a measure of the resistance offered to cutting. Its applicability is limited to comparatively soft steels or other metals softer than hardened carbon steels or hard alloy steels. Its range of usefulness on comparative tests is rather limited, owing to the fact that the pressure and the rate of revolution must be changed if the metals tested are of greatly different characters.

RELATIONS BETWEEN THE TENSILE STRENGTHS OF VARIOUS STEELS AND THEIR HARDNESSES (ABBOTT)

Kind of Steel.	Ultimate Strength in 1000 lb./in.^{2} (M) in Terms of		Relation of Brinell Hardness Number to Scleroscope Hardness Number.
	Brinell Hardness Number (B).	Scleroscope Hardness Number (S).	
Carbon steel	$M_t = 0.73B-28$	$M_t = 4.4S-28$	$B=5.6S+14$
Nickel steel	$M_t = 0.71B-32$	$M_t = 3.5S-6$	$B=5.0S+48$
Chrome-vanadium steel . .	$M_t = 0.71B-29$	$M_t = 4.2S-21$	$B=5.5S+27$
Low-chrome-nickel steel . .	$M_t = 0.68B-22$	$M_t = 3.7S-1$	$B=5.4S+33$
High-chrome-nickel steel .	$M_t = 0.71B-33$	$M_t = 3.7S-3$	$B=4.8S+58$
All steels grouped together	$M_t = 0.70B-26$	$M_t = 4.0S-15$	$B=5.5S+28$

Tests of the resistance of steel to wear caused by dry rolling friction have been made but the results of such tests do not agree very closely with the hardness determination made by the Brinell or scleroscope methods, as is in fact to be expected, since the resistance of a material to wear is a quite different property from its resistance to indentation or its resiliency.

In concluding the discussion of hardness of steels and the various methods of measuring hardness, it may be remarked that the hardness test is finding a constantly widening field of application. It can be used to test articles like castings, forgings, etc., without impairing their subsequent availability for use. It can also be used advantageously in exploring different portions of a finished article to ascertain the varying effect of cooling conditions, working, etc., upon the character of the metal.

138. Ductility of Steels as Indicated by Cold-Bending. The indication of the ductility of steel which is afforded by a simple cold-bending test is very valuable and significant, and the test possesses the advantage of being one which can easily be made without special appliances. Cold-bending is accomplished either in a vise, or an anvil, or with a steam hammer or hydraulic press. According to the severity of the test desired the bend may be made over a sharp edge, or about a pin or template of any desired radius. The relative extent to which various classes and grades of steels are expected to stand cold-bending is indicated by the following summary of the specifications of the American Society for Testing Materials:

STANDARD SPECIFICATIONS FOR COLD-BENDING TESTS OF VARIOUS STEELS

Character and use of steel.				Cold bend.
Bridge, building, car, and locomotive structural steel			Not over ¾ inch thick	180° d = 0
			¾ inch to 1¼ inch thick	180° d = t
			Over 1¼ inches thick	180° d = 2t
Rivet steel for bridges, buildings, boilers, ships, etc.				180° d = 0
Ship structural steel			Not over ¾ inch thick	180° d = t
			¾ inch to 1¼ inches thick	180° d = 1½t
			Over 1¼ inches thick	180° d = 2t
Soft steel castings (specimens are 1 inch by ½ inch section)				120° d = 1 in.
Medium steel castings (specimens are 1 inch by ½ inch section)				90° d = 1 in.
Boiler and firebox steel			Not over 1 inch thick	180° d = t
			Over 1 inch thick	180° d = 2t
Billet steel concrete reinforcing bars	Plain bars	Structural Grade	Under ¾ inch thick	180° d = t
			¾ inch thick or over	180° d = t
		Intermediate Grade	Under ¾ inch thick	180° d = 2t
			¾ inch thick or over	90° d = 2t
		Hard grade	Under ¾ inch thick	180° d = 3t
			¾ inch thick or over	90° d = 3t
	Deformed bars	Structural grade	Under ¾ inch thick	180° d = t
			¾ inch thick or over	180° d = 2t
		Intermediate grade	Under ¾ inch thick	180° d = 3t
			¾ inch thick or over	90° d = 3t
		Hard grade	Under ¾ inch thick	180° d = 4t
			¾ inch thick or over	90° d = 4t
Cold-twisted bars			Under ¾ inch thick	180° d = 2t
			¾ inch thick or over	180° d = 3t
Concrete reinforcing bars from rerolled rails	Plain bars		Under ¾ inch thick	180° d = 3t
			¾ inch thick or over	90° d = 3t
	Deformed bars		Under ¾ inch thick	180° d = 4t
			¾ inch thick or over	90° d = 4t

(*d* = diameter of pin about which specimen of thickness *t* is bent.)

139. Behavior of Steel under Impact. Shock Resistance. The impact strength of steels is a matter of great interest to engineers, because the construction uses of the material in situations where some measure of impact is not encountered are very few. In view of this fact it is evident that the static load tests usually applied possess only a limited value if they fail to give any indication of the ability of the material to withstand the effect of suddenly applied loads. The amount of published experimental data bearing on this question is rather meager, and it is impossible to harmonize much of that which is available on account of the great variation in the methods used by experimenters both as regards apparatus and size and form of test specimen.

Many types of impact testing machines have been designed but very few of them have found more than local use for very special tests.

A special form of transverse impact test is the drop test of steel rails. In this test a heavy tup is allowed to fall upon the center of a short section of rail supported upon a span of 3 feet. The height of drop is dependent upon the weight of the rail under test.

A type of impact testing machine that is receiving considerable attention, determines the amount of work necessary to fracture a small test specimen by a sudden blow; both tension and transverse loading are used. The load is applied by a falling pendulum or weight. The test specimen is usually notched.

140. Behavior of Steels under Repeated and Alternating Stresses. Fatigue. That all metals may ultimately fail under repeated stresses far below the ultimate strength shown by the conventional tensile or compressive test is a fact which is well known. Such failures have often been observed in the case of axles of car-wheels, parts of moving machinery, etc., and the phenomenon has frequently been demonstrated in a scientific manner since the pioneer work begun by Wöhler in 1849 and reported in 1870. If the maximum stress approximates closely the ultimate strength, failure may, in the case of steels, be induced by very few repetitions; with a maximum stress not far from the elastic limit, from a few thousand to several hundred thousand repetitions may be required; and if the maximum stress does not greatly exceed one-half the elastic limit, rupture, if ever attained, will usually be produced only by millions of repetitions.

This phenomenon, common to all metals possessing any considerable elastic properties, was once ascribed to a general deterioration of the cohesion between crystalline constituents of the metal when subjected to many repetitions or reversals of comparatively low stresses. Owing probably to this idea of deterioration, the phenomenon came long ago to be known as the "fatigue" of metals, and the use of the term has persisted in spite of the fact that it is now known to be a process of gradual and progressive failure or fracture of the crystals themselves.

Examination under the microscope of the behavior of the crystalline constituents of steels under stress, or the effect of high stresses upon their form and structural integrity, has shown that crystalline failure is usually a gradual process and not an instantaneous one. Whatever the character and manner of application of the external force acting on a piece of steel, the individual crystals are subjected either to tension or shear, and failure of the piece as a whole is a matter of the successive failure of individual crystals. Failure very seldom occurs at crystalline boundaries.

The actual determining factors in fixing the average stress under which steel will rupture are: the stress to which the most stressed crystals are subjected; the behavior of these crystals under load, and the extent to which the failure of a limited number of crystals affects the structural integrity of the piece as a whole.

The stress to which the most stressed crystals are subjected under the action of a given external load is dependent chiefly upon the uniformity of distribution of stress between crystals, which in turn is dependent upon the homogeneity of the structure. The preëxistence of internal stresses, originating during cooling, heat treatment, or mechanical working, is a factor which cannot be neglected but which cannot be taken account of quantitatively.

The failure of ductile crystals under stresses exceeding their yield point is really a succession of shear slips on parallel planes of least strength. It is not altogether sudden, because after a slip occurs on one plane a new slip occurs on an adjacent plane. This is followed by a third slip, and thus the action proceeds, the ultimate plastic deformation of the crystal being made up of very small permanent slips on many slip planes. The plastic yielding of the softer crystals may radically change the stress conditions of the surrounding crystals which are still behaving elastically, and thus greatly affect the subsequent extent of variation of stress in the material.

The harder crystalline constituents of steels fail on planes of weakness in essentially the same manner as do the softer and more ductile crystals, but the fact that they possess a very high elastic limit causes failure to follow very soon after the proportionality of deformation to stress is lost. Their failure is in consequence considered sudden and they are called brittle.

The possibility of failure of crystals in tension instead of shear is dependent upon the orientation of the crystals with respect to the direction of stress. Moreover, since this is wholly a matter of chance, and the interactions between crystals are very complex, the possibility of tensile failure of crystals being an important factor in the ultimate breakdown of the crystalline aggregate is probably remote.

The extent to which the failure of a limited number of crystals affects the structural integrity of the piece as a whole is dependent chiefly upon the manner in which the stress is externally applied, being greatest when the distribution of stress is least uniform. Thus torsion loading is probably most hazardous, transverse loading slightly less so, and tensile loading most conducive to the attaining of a high average ultimate strength.

In the ordinary tension test, the load being gradually and perhaps continuously increased until rupture occurs, conditions are most favorable to high ultimate strength because of the opportunity afforded for adjustment of deformation under the action of the load. Especially after the yield point has been reached does this tendency toward equalization of stress become operative.

When, on the other hand, a load causing an average stress far below the ultimate strength is applied many times in succession, each occurrence of stress probably produces minute permanent shear slips which, if the load is not excessive, will at first be principally confined to the particular crystalline constituents whose limit of elastic behavior has been passed, owing to non-uniform distribution of stress or the preëxistence of internal stresses. Further repetitions of stress not only produce more shear slips, but the cumulative effect of failures of individual crystals upon the uniformity of stress distribution probably means a gradual increase in the extent of the destructive action caused by each stress repetition. The number of repetitions of stress necessary to cause failure appears to be a function of the average intensity of stress repeatedly applied, but is also dependent upon the character, prevailing size, and structural arrangement of the crystalline constituents of the metal.

As the percentage of carbon is increased the proportion of relatively coarse crystals of ferrite decreases and the endurance of steels under repetitions of stress normally tends to increase until the carbon content approaches the eutectoid ratio. The relation of carbon content to the endurance of steels is very often masked, however, by the effect of other factors. Thus any heat treatment which tends to increase the size of crystals formed is very detrimental to endurance, and the presence of comparatively large amounts of phosphorus, manganese, etc., or the existence of internal stresses caused by the conditions of cooling, heat treatment, or mechanical working, may be factors whose influence outweighs that of carbon content.

Methods of subjecting steel to tests of its endurance have not yet been standardized. Many methods of making endurance tests have been proposed, and many fatigue-testing machines are on the market, yet very few have received much general attention.

141. The Magnetic Properties of Steel. The magnetic properties of iron and steel are of great practical importance.

Large quantities of iron and steel are used in the construction of electrical machinery, motors, generators, transformers, etc., where the magnetic properties of the material used are of supreme importance.

The magnetic properties and mechanical properties of irons and steels are dependent upon the same factors, i.e., composition, heat treatment, mechanical working, etc. The mechanical properties can therefore, at least in a measure, be foretold by the results of magnetic testing.

Relation between Magnetic Properties and Chemical Composition

The following conclusions have been arrived at by de Nolly and Veyret as the result of an investigation of the hysteresis and eddy current losses of dynamo sheet metals of varying chemical composition.

Carbon. "The carbon percentage should be as low as possible and always remain below 0.1 per cent." A 0.15-per-cent-carbon steel is greatly inferior to one containing 0.10 per cent carbon.

Silicon. "The presence of silicon diminishes the hysteresis losses considerably. The coefficient η changes from 0.0016 for an iron free of silicon to 0.0009 for a metal containing 3.5 per cent silicon." Silicon also increases the resistivity of the steel and therefore reduces eddy current losses. In a very weak field silicon increases permeability, but with stronger magnetizing force the effect is reversed and permeability is diminished.

Manganese. Manganese appears to be detrimental to magnetic properties if present in amounts exceeding about 0.3 per cent. The data secured bearing upon the effect of manganese are not very conclusive.

Sulphur and Phosphorus. Both sulphur and phosphorus were found to be elements whose presence in amounts exceeding about 0.3 per cent (for both combined) constitute a distinct injury to magnetic properties.

Relation between Magnetic Properties and Temperature

Investigation of the changes in magnetic properties of steels as the temperature of the specimen under test is raised or lowered has been made in only a few instances, and little detailed information is available. An extensive study was made in the Chemical Laboratory of Messrs. Schneider's Works at Creusot, and the following remarks are based wholly upon this work.

The method of study followed consisted in subjecting steel specimens of various forms to uniformly increasing and decreasing temperatures in an electric furnace, and simultaneously exposing them to a chosen constant magnetizing force. The temperature indications of a thermocouple mounted in the specimen, and the corresponding intensity of induced magnetism were continuously recorded autographically on a curve, the ordinates to which are values of $\mathcal{B}$, and the abscissæ temperatures in degrees.

One of the facts most emphatically shown by the test results was that the form of the curve obtained varies considerably for specimens of different forms. The maximum strength of magnetizing force employed also had a marked effect upon the character of the temperature-inductance curve.

The specimens used in the series of tests were 200 millimeters long, 3 millimeters in diameter, and comprised a series of six steels varying in carbon content from 0.06 per cent to 1.20 per cent. The maximum strength of field employed was 20 gausses and the frequency 45 cycles per second.

The most pronounced change of magnetic properties occurs when the critical range of temperatures is reached, at which point an almost total loss of magnetism takes place.

Aside from the great change in magnetism which takes place in passing the critical range of temperatures, other changes of lesser magnitude occur at lower temperatures. In the case of the three steels of lowest carbon content there is a progressive increase in induction up to a temperature of about 200° C. (392° F.) or 250° C. (482° F.).

All of the medium- and high-carbon steels exhibit a certain falling off in magnetism in passing through the range just below 200° C. (392° F.), the loss becoming accentuated as the percentage of carbon increases. This behavior appears to be due to the fact that iron carbide loses its magnetism to a very large degree at a temperature in the neighborhood of 200° C. (392° F.). The phenomenon is naturally most marked therefore when the total carbon content and therefore the carbide content is greatest.

Relation between Magnetic Properties and Mechanical and Thermal Treatment

Cold working is injurious to the magnetic properties of steel in proportion to the amount of distortion. Annealing at 300° C. (572° F.) removes the injurious effect of cold working in a measure, but is less effective than annealing at higher temperatures.

142. The Corrosion of Iron and Steel. The importance of the durability of iron and steel when exposed to the various conditions of service has long been recognized. Unfortunately, much of the literature of the subject is of a distinctly controversial nature, owing to the fact that students of the subject are far from being agreed upon what the true explanation of the phenomenon is. Furthermore, various experimental studies of the relative corrodibility of different materials have, because of their contradictory results, led to opposing conclusions concerning the effect of various factors such as relative composition, constitution, structure, etc.

The end product of the process of corrosion, i.e., rust, is well known to be ferric oxide plus a variable amount of combined water, and all authorities are agreed that corrosion of iron is possible only when both oxygen and water are present. Iron will not rust in perfectly dry air; on the other hand, it cannot rust in water which is entirely free from oxygen. It is further well known that certain conditions encountered in practice, such as a very humid atmosphere, exposure to acid fumes, acid-bearing air or waters, or water containing dissolved salts, tend to accelerate corrosion. At about this point universal agreement between authorities ceases to exist and it becomes necessary to recognize the existence of conflicting theories. The following brief discussion of these theories is based principally on the works of Dr. A. S. Cushman, Director of the Bureau of Industrial Research in Washington, D.C.

Of the many theories advanced to account for corrosion three have gained widest recognition. These are, in the order of their present importance: (1) the electrolytic theory, (2) the hydrogen peroxide theory, and (3) the carbonic acid theory.

The Electrolytic Theory of Corrosion. Cushman and Gardner have concisely stated the electrolytic theory of corrosion in the following terms: "Iron has a certain solution tension, even when the iron is chemically pure and the solvent pure water. The solution tension is modified by impurities or additional substances contained in the metal and in the solvent. The effect of the slightest segregation in the metal will throw the surface out of equilibrium, and the solution tension will be greater at some points than at others. The points or nodes of maximum solution pressure will be electro-positive to those of minimum pressure, and a current will flow, provided the surface points are in contact, through a conducting film. If the film is water, or in any way moist, the higher its conductivity the faster the iron will pass into solution in the electro-positive areas, and the faster the corrosion proceeds. Positive hydrogen ions migrate to the negative areas, negative hydroxyls to the positives."

"If the concentration of the hydrogen ions is sufficiently high, the hydrogen ions will exchange their electrostatic charges with the iron atoms sweeping into solution, and gaseous hydrogen is seen escaping from the system. This takes place whenever iron is dissolved in an acid. If, however, as is usual in ordinary rusting, the acidity is not high enough to produce this result, the hydrogen ions will polarize to a great extent around the positive nodes without accomplishing a complete exchange. This polarization effect resists and slows down action. Nevertheless, some exchange takes place and iron slowly pushes through."

From the above discussion it must be apparent (if the electrolytic theory is accepted) that the relative corrodibility of irons and steels under given conditions of exposure to air and moisture, with or without the accelerating effect of acid, will be in a large degree a function of their relative chemical purity and structural homogeneity. It is very difficult to demonstrate these propositions experimentally, however, because of the complexity of the problem and the limitations imposed upon the investigator in his efforts to eliminate all factors except the one under special study.

One of the favorite methods of investigating the relative corrodibility of various irons and steels has been by acceleration tests, the media employed being an acid solution which, compared with the ordinary conditions of rust formation, is a very potent electrolyte. It may well be doubted whether the comparative results obtained under such circumstances can be relied upon as a certain indication of the behavior of the materials under the conditions of natural rust formation. Nevertheless it is probable that accelerated tests carefully conducted do indicate certain general tendencies which have an important bearing upon the practical problem of how irons and steels may best be made and handled to produce the least corrosive material.

The carbonic acid theory asserts that the hydroxylation of iron cannot take place without the interaction of carbonic or some other acid. The acid changes the metal to a ferrous salt with evolution of hydrogen:

$$2\,Fe + 2\,H_2CO_3 = 2\,FeCO_3 + 2\,H_2.$$

The water and oxygen now react with the ferrous salt, forming ferric hydroxide and setting free all the acid originally used:

$$2\,FeCO_3 + 5\,H_2O + O = 2\,Fe(OH)_3 + 2\,H_2CO_3.$$

A small amount of acid is sufficient to rust a large amount of iron, because it is set free again immediately after having combined with the iron to form the ferrous salt.

This explanation of corrosion is entirely plausible, and the fact is well known that acids do often act a part in promoting the corrosion of iron, but the theory has been discredited by a number of investigators, including Cushman, who have shown, by methods so carefully planned and executed as to leave scarcely room for questioning the accuracy of their results, that iron will corrode in water containing oxygen, but not a trace of carbonic acid. Corrosion will even take place in dilute alkaline solutions in spite of the fact that the alkali would neutralize any acid present.

The hydrogen peroxide theory explains corrosion by stating that water and oxygen react with iron to form ferrous oxide and hydrogen peroxide, whereupon one-half of the peroxide combines with the ferrous oxide to form hydrated ferric oxide, the excess of peroxide remaining to form a further amount of rust. Thus:

$$2\,Fe + 2\,O_2 + 2\,H_2O = 2\,FeO + 2\,H_2O_2 = Fe_2O_3,H_2O + H_2O_2.$$

This theory has failed to gain any substantial corroboration as the result of experimental investigation, and is largely discredited by the fact that the most delicate tests have always failed to detect even the transitory presence of the peroxide during the ordinary process of rusting.

CHAPTER IV

CAST IRON

143. Cast Iron as a Material of Engineering Construction. Cast iron differs markedly from the other general classes of iron products — wrought iron and steel — both in chemical constitution and in physical characteristics. It possesses a very complex constitution which is extremely subject to variation with slight variations in details of manufacturing processes; it is comparatively coarsely crystalline in structure, possesses considerable hardness, but lacks toughness, melts readily and passes suddenly into a very fluid state, in which condition it will take a quite perfect impression of a mold, but it is non-ductile at all temperatures and cannot be deformed (as in forging operations) without being broken.

Cast iron is not used structurally to nearly the extent to which both wrought iron and steel are so used. It is used to a certain extent, however, for columns and posts in buildings, also for column bases, bearing plates, and innumerable minor structural parts. In machine construction it finds its widest field of application, for no other metallic material which can be cast in complex forms can be produced with such ease and at so low a cost. In this field its principal competitors are malleable cast iron, cast steel, and cast brasses, bronzes, etc. Each of these materials possesses valuable properties not possessed by cast iron, such as greater strength, toughness, or non-corrodibility.

144. Iron Melting in General. A certain small amount of iron castings are made by running the metal into molds just as it comes from the blast furnace. Ingot molds, for instance, are made in this way at steel works. The variability of the blast-furnace product, however, and the difficulty in judging the character and correcting the composition of the molten pig iron, limits the making of "direct castings" to a rather restricted class of products. The bulk of all the iron used as "cast iron" is remelted either in the "cupola furnace" or the "air furnace" before being cast in molds.

The process of remelting the iron in the cupola resembles the process of melting ore in the blast furnace, but the reducing action of the blast furnace is not here present. The only office of the air blast used is the oxidation of the fuel of the charge. Remelting in the air furnace bears no resemblance to cupola melting, since the charge is melted in a hearth out of contact with the fuel. The heat is supplied by radiation and reflection from the flame of a soft coal fire maintained in a firebox adjoining the hearth.

THE MATERIALS USED

145. Foundry Pig Iron. Pig irons used for foundry purposes are nearly all bought by analysis, the content of silicon and sulphur being specified, and sometimes also the total carbon, manganese, and phosphorus.

In addition to the irons properly classed as foundry pig irons, Bessemer pig, ferro-silicon, and a few other special pig irons are used at times to bring the composition of the cast iron within the required limits.

146. Scrap Iron. The term "scrap iron" is used to designate that considerable portion of the iron charged into the furnace which has been remelted one or more times. It consists mainly of castings discarded after having been in service, but includes also defective castings, gates, sprues, etc. Some classes of castings are made without any scrap. For others, the percentage sometimes runs as high as 30 or 40 per cent.

147. The Flux. The office of a flux in the melting of iron is to absorb and carry off in a slag the non-metallic residue of the iron and the ash of the fuel, and to assist in the removal of sulphur. Since the impurities in the charge of the melting furnace constitute only a very small proportion when compared with the amount present in the charge of the blast furnace, the percentage of flux required is correspondingly small. The requirements vary greatly, but in general will average in the neighborhood of from ½ to 1½ per cent of the weight of the iron.

The flux used is calcium carbonate, usually in the form of limestone, but oyster shells, marble chippings, dolomite, etc., are sometimes used, and a portion of fluorspar (CaF_2) is often added to obtain a more liquid slag.

148. The Fuel. The office of the fuel in iron melting is simply as a source of heat.

Coke is most commonly used as fuel in the cupola, although a mixture of coke and anthracite coal is sometimes used. The air furnace requires the use of a long-flaming bituminous coal or gas.

The fuel requirements depend upon the character of the castings being made, small and thin castings requiring a hotter metal than large castings.

THE FURNACE

149. The Cupola Furnace and Its Equipment. The cupola in its essential arrangement is really a small blast furnace, operated under a very much lower blast pressure, and intended only to melt the charge without any attempt being made to attain reducing conditions.

The type of cupola shown in Fig. 41 is representative of the cupolas used in foundries and in steel works. It consists of a vertical cylindrical shell of wrought iron or steel, lined with firebrick set in fireclay grout. The structure is supported on four columns about four feet from the floor. The size of the cupola is quite variable, ranging from about 22 inches inside diameter to about 100 inches. The height is dependent upon the diameter, the usual practice being to locate the charging door at a height above the bottom plate equal to from 3½ to 4 times the internal diameter. The height of the stack above the charging door is governed by considerations of draft.

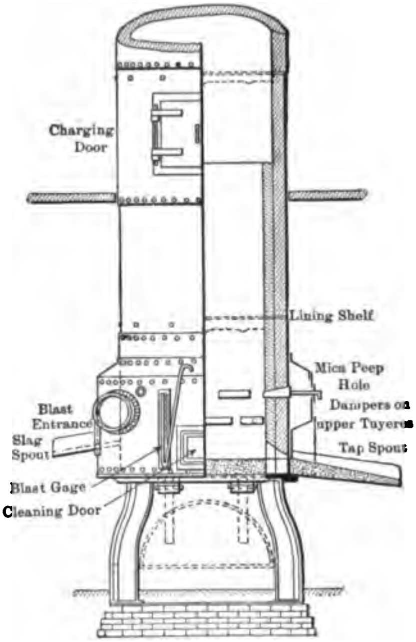

Fig. 41. — Foundry Cupola

The air blast enters the crucible through tuyères leading from the "wind belt" or "air chamber" which surrounds the lower portion of the furnace. The tuyères themselves are not elaborately constructed, but are usually simply iron castings set in the brickwork of the lining. The tuyères are usually arranged in two horizontal rings some 12 or 15 inches apart vertically, the area of the upper tuyères being only a small fraction of that of the lower ones as a rule.

The slag hole is situated just below the tuyères at a height above the bottom plate, governed by the amount of metal required per heat.

The bottom of the furnace consists of two or more flap-hinged castings which are normally held in position by a prop beneath. At the conclusion of a "heat" or "cast" the prop is knocked out, allowing all the material remaining in the furnace to be "dumped."

The "tap-hole" or "spout" is located just at the level of the bed of sand which covers the bottom doors.

The air blast is usually derived by use of a positive-acting blower, usually of the two-impeller type. This type of blower is very simple, free from mechanical weakness, and is capable of delivering large quantities of air under low pressures.

150. The Reverberatory or Air Furnace. The reverberatory or air furnace uses natural draught, and employs the principle of utilization of heat derived by reflection from the roof upon the bath of the metal.

The design of air furnaces shows many variations, but Fig. 42 shows a typical form. The main portion of the furnace, the hearth (*f*), is flanked on one end by a firebox (*g*), and on the other by a flue leading to a stack (*o*). The walls of the furnace (*a*) are of very heavy brick masonry, incased in iron plates (*b*), and reinforced both ways by tie rods (*c*) between buckstays (*d*).

The hearth bottom is a mixture of sand and fireclay supported by brickwork built to slope downward from the "fire bridge" (*h*) to the flue bridge. The "crown" of the furnace is similarly inclined downward toward the stack in order to deflect the heat of the flames downward on the iron in the hearth.

The firebox is provided with iron grate bars, and fuel is introduced through a fire-door in one side wall of the firebox. Pig iron and scrap are charged in through the charging door (*j*), and holes (*m*) are provided to facilitate the skimming of the bath of metal. The spout is not shown in the figure, but is so placed as to drain the metal from the lowest part of the hearth.

Furnaces in which large amounts of iron, or bulky scrap iron, are melted often have removable sections in the crown through which the charge is lowered by cranes.

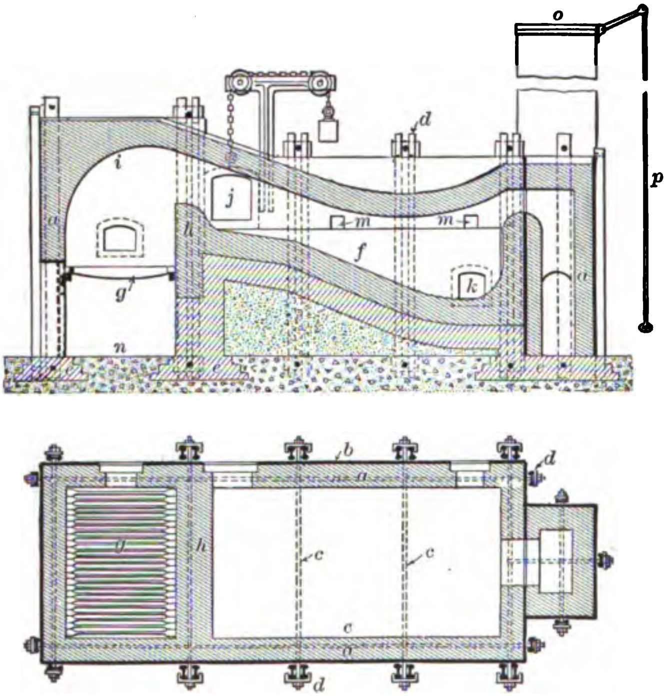

FIG. 42. — Air furnace.

151. Relative use of Cupola and Air Furnace. The cupola is used for most foundry purposes in the production of gray iron castings and for melting iron for steel furnaces. The use of the air furnace is principally confined to the production of white iron for malleable cast iron, but it is also used to produce irons of particular composition for special purposes.

OPERATION OF CUPOLA

152. Starting the Furnace. The usual method of starting consists in laying a bed of shavings and kindling-wood on the bottom, followed by heavier wood and then fine coke, and lastly a charge of the regular fuel.

The tuyère doors are now opened, the shavings lighted at the front, and the fire allowed to burn up until all the fuel is well lighted. Then the tuyère doors are mostly closed and charging is begun.

An oil torch is sometimes employed without the use of wood kindling. Openings or flues through the coke are made directly upon the sand bed by the use of thin boards, and the fuel is ignited by the torch flame entering at the front.

153. Charging. The bed of fuel having been properly prepared and leveled off, the charge of broken pig and scrap is carefully placed, an effort being made to fill up the interstices as far as possible and keep the charge level. The next charge of fuel is now placed on the iron, and alternate charges of iron and fuel continue until the height of the charging door is reached. When a flux is required, the proper proportion is charged on top of each bed of iron, except at the start and at the end of the heat, when it may be omitted.

The charging of the furnace is often done two or three hours before the blast is started but, even if the blast is put on immediately after charging the iron, iron should begin to melt and appear at the tap-hole within fifteen or twenty minutes after starting the blast. If it does not, it indicates that the bed of coals has not been properly prepared.

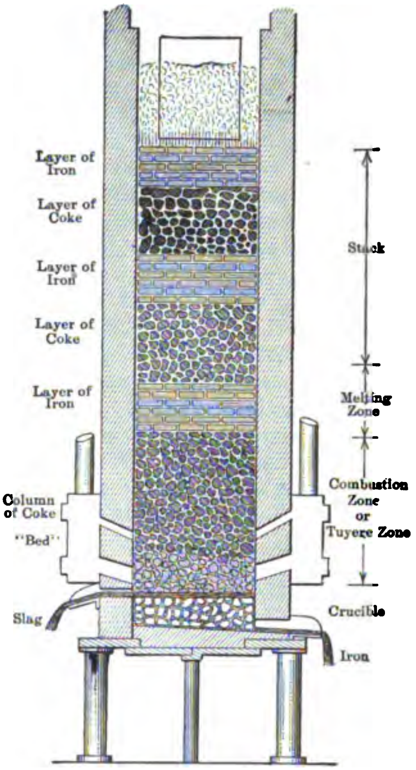

Fig. 43. — Zones in Cupola. (Stoughton.)

154. Action within the Furnace. When the furnace is properly operated it shows the following distinct zones of action, beginning at the bottom and proceeding upwards: The crucible zone or hearth, the tuyère zone, the melting zone, and the stack. These four zones are indicated in Fig. 43.

The crucible zone extends from the bottom up to the level of the tuyères. It serves the sole purpose of collecting and holding the molten metal and slag until tapped out. If the metal is allowed to run out of the spout continuously, this zone will be very short, the tuyères being very close to the bottom. If the tuyères are located high in the hearth a bath of considerable depth may be allowed to accumulate, but because of the cooling action of the blast from the tuyères, it will not be as hot iron as that obtained by collecting the metal in a ladle outside of the furnace. If slag is formed and allowed to collect on the bath of metal it will help to protect the latter from the effect of the blast.

The tuyère zone is the zone of combustion. The blast here comes in contact with the red-hot coke and rapidly oxidizes it. A column of coke always extends from the melting zone to the bottom of the crucible, and combustion occurs from the level of the molten metal to a point above the tuyères, the height of which is dependent upon the pressure of the blast. The blast pressure should not be sufficient to make the top of this zone more than 15 to 24 inches above the uppermost tuyères. This pressure varies from about 1 pound per square inch for the largest cupolas, to about ⅓ pound per square inch for the smallest ones.

The melting zone is situated directly above the tuyère zone. During the melting the iron is supported on a column of coke, extending to the bottom of the cupola, which is the only solid material below the melting zone. The iron as it melts trickles down to the bottom over the column of coke. Each layer of iron requires about 5 to 10 minutes to melt, and the column of coke is constantly sinking, so that the last of the iron melts several inches lower than the first. If the charges of iron and coke and the pressure of the blast are properly proportioned, each charge of iron will enter the top of the melting zone just before the last charge is completely melted at the bottom.

The stack extends above the melting zone to the level of the charging door. Its function is to contain material that will absorb heat to bring it into good condition for action in the melting zone, and to keep the heat in the melting zone as much as possible.

The amount of air required for satisfactory operation is largely in excess of the amount theoretically required to burn the coke, on account of imperfect combustion and leakage.

155. Duration of the Cupola Run. A foundry cupola is never run continuously, but is started anew for each casting and is "dumped" at the conclusion of the run. As a general rule the duration of the run does not exceed three or four hours, and it cannot exceed this period if no provision is made for draining off the slag. Some large cupolas operated in connection with steel plants are run continuously for six days in a week, at the end of which time, if not before, stopping is generally required to effect extensive repairs.

156. Tapping Out and Stopping In. The tap-hole is usually left open until the iron begins to run after the blast is started, at which time it is closed if an accumulation of metal is desired. Often the first iron is used only to warm the ladles which are subsequently to be employed in pouring the castings.

The "stopping in" is accomplished by the use of the "bod" and "bod-stick." The bod is a plug made of fireclay, sand, or molding sand, molded in the shape of a cone which adheres to the enlarged end of the "bod-stick," the latter being simply an iron bar with an upset end. The bod is thrust in quickly to stop the flow of metal and bakes hard enough to withstand the pressure. A soft bod of molding clay and sawdust is used when the cupola is tapped and stopped very frequently.

Tapping consists simply in piercing the bod by use of a round iron bar provided with a pointed end. It is an operation requiring great care, since the danger of causing molten iron to spill and burn those near at hand is ever present.

OPERATION OF AIR FURNACE

157. The Charge. The small scrap is first placed in the furnace hearth, followed by the flux and the pig iron or the large scrap. The furnace is either still hot from the last melt, or it is heated for some hours before charging, so that melting begins soon after the charge is placed.

158. Control of Melting. The temperature of the furnace is controlled by the regulation of the draft by means of a damper in the stack or stack flue, and one in the firebox. The bituminous coal burns with a long flame which sweeps through the melting chamber, the conditions being strongly oxidizing rather than reducing. A slag soon forms and covers the metal as it accumulates, so protecting it in a measure from oxidation. The slag is not drained off, but must be skimmed from time to time. The furnace man also rabbles the charge, gradually pushing the pig down into the bath.

The time required for melting is much greater than in the case of the cupola, the actual time being dependent upon the capacity of the furnace. A 10-ton furnace will melt down a charge in three or four hours, while a 30-ton furnace will require eight or nine hours. The fuel requirement is about one-fourth the weight of the charge or about 35 per cent of the iron produced. The metal is tapped as rapidly as possible and, since the hottest metal is at the top of the bath, a series of tapholes at different levels are sometimes used successively. The loss of metal due to oxidation amounts to from 2 to 5 per cent of the charge.

159. Advantages and Disadvantages. The product of the air furnace is purer than cupola iron, since the metal does not come in contact with the fuel. This means less absorption of sulphur and less absorption of carbon, resulting in general in a higher grade and stronger iron. The process being much slower than the cupola process, it is under better control and any desired composition can be more closely approached.

The cupola, on the other hand, is a cheaper installation, requires less skillful management and is therefore cheaper to operate, the heat is more uniform so that all the metal of a melt has more nearly the desired temperature, very hot iron is more easily obtained, the furnace can be started and stopped more readily, the fuel efficiency is greater, and there is less loss of metal through oxidation and consequent removal in the slag.

IRON FOUNDING

160. Iron Founding in General. The art of founding consists in pouring molten metal into a mold of any desired special form, which the metal assumes and retains when cold.

The most important part of iron founding is making the molds, a process which demands a very high order of mechanical skill and no small amount of manual labor.

No portion of the technology of iron is of more importance to the engineer and machine designer than a thorough understanding of the molder's art. Sand, the material almost universally used for molds, cannot be molded into any conceivable shape, but has certain practical limitations. For the most part, the impression in the sand of the mold is made by a pattern which must be so designed that its removal from the mold is possible. It is not as easy as it may first appear to avoid shapes which would call for a pattern which could not possibly be removed, leaving the mold intact. Another consideration is that sand, when confined, is a comparatively unyielding material, and therefore the shape of castings must be such that the shrinkage which invariably occurs as the metal cools will not induce dangerously high internal stresses.

Without mentioning any of the other factors it will be clear that the definite limitations of the molder's art constitute certain limitations for the engineer, and without a practical knowledge of the former iron castings cannot be intelligently designed.

161. Molds and Molding. The various methods of making sand molds may be divided into the following three classes of greatest importance: "green-sand molding" involves the making of an impression of the desired form, by means of a pattern, in a mold composed entirely of sand in a damp state; "dry-sand molding" involves the making of molds in damp sand by means of a pattern as in green-sand molding, after which the mold is dried in an oven until the moisture is expelled and the sand baked hard; "loam molding" does not involve the use of patterns, but its application is largely confined to articles whose surface are surfaces of revolution, the molds being built up of brickwork covered by a layer of loamy sand in which the desired imprint is made by a "sweep." Machine molding may replace hand work by either of these methods.

162. Patterns and Cores. Pattern-making is an art in itself involving a considerable amount of technical skill. Patterns may in general be divided into two classes, the first of which are used to produce solid castings, the second to produce hollow castings. In most cases, however, the pattern is solid, the hollow portion being formed by a "core" which is placed in the mold after the removal of the pattern.

The great majority of all patterns are made of wood. Brass or other metals are sometimes used, however, for the sake of greater durability when a great many molds are to be made from the same pattern. The simplest patterns are merely solid wood duplicates of the desired castings except that an allowance of about ⅛ inch per foot is made in dimensions to compensate for the shrinkage of the castings in cooling. A slight tapering known as draft is given the vertical plane surfaces in order to facilitate the withdrawal of the pattern from the mold.

The cores are usually made from a mixture of fine siliceous sand with clay or loam, which is packed in the core-box while damp. Some binder such as flour and water, rosin, or glue-water, is usually required to give the core strength enough to permit handling, and holes are usually left running lengthwise through the core for the purpose of venting. When the cores are dried in an oven prior to use in a mold they are called "dry-sand cores." The great majority of all cores are of this class. If a core is long, particularly if it is supported horizontally over a considerable span, it is necessary to stiffen the core by insertion of iron or steel wires or even skeleton frames of metal. Cores which are adjacent to thick parts of a casting are apt to be fused, unless protected from the heat of the slowly cooling molten metal. They are therefore often daubed with an insulating coating of "blackening." For this purpose pulverized graphite or plumbago is either applied wet as a wash, dry with a brush, or shaken from a cloth bag.

163. Chilled Castings. A "chilled casting" is one made in a mold, some parts of which, at least, are made of iron, such portions of the mold being called "chills." The purpose of introducing chills into a mold is to convey away the heat of the molten metal rapidly, a treatment which has the effect of causing the carbon in the iron to remain in chemical combination, instead of separating therefrom in the form of graphite, as it normally does in slowly cooled castings of gray iron. The physical effect of chilling on the character of the iron is to greatly harden it for a certain depth, giving to the exterior of the iron the characteristic appearance of white iron, while the body of the casting remains a gray iron. Chilling is principally used for wearing surfaces of such castings as iron rolls and treads of car wheels.

164. Pouring the Iron. In small foundries it is usually the practice to stop molding in the middle of the afternoon and pour off all the molds that have been made. For small work the metal is caught in hand ladles at the cupola tap-hole and conveyed to the molds by one or two men. The ladles must be heated by allowing a part of the first iron run to stand in them for a few moments before the actual pouring is begun; otherwise the ladle will chill the metal and the iron will not enter the mold at the required temperature. Practically all foundry ladles are "top-pouring" (i.e., the metal is poured by tipping the ladle), rather than "teeming" ladles, which are provided with a valve in the bottom. This necessitates the use of a bar to keep back the slag which floats on the metal and would otherwise enter the mold. Care is exercised by the molder to hold the ladle as near the pouring gate as possible to lessen the impact of the stream of metal upon the sand of the mold. The proper time to cease pouring is indicated by the appearance of the metal at the top of the riser. Each mold must be filled in one operation, and therefore when the ladle does not contain enough metal to completely fill a mold its contents are emptied into pig-beds molded on the foundry floor.

Larger foundries employ traveling cranes and large ladles holding perhaps a ton or more of metal. During the filling of the molds, it is usually the practice to ignite the gas which escapes from the vent holes, thereby preventing accumulation of the gas in the molding room.

The flasks are removed soon after the completion of the pouring, and the molds are dumped off the bottom boards in piles, from which the hot castings are hooked out and allowed to cool. The gates and runners are now broken off by a few sharp blows with a hammer and the castings removed for cleaning.

165. Cleaning the Castings. The sand which adheres to the castings is usually removed by one of three methods: rattling them in a "tumbling barrel," pickling, or sand blasting.

Rattling is most commonly practiced in case of small castings. The tumbling barrel is simply a short horizontal cylinder which is mounted on trunnions. The castings are piled into the barrel, together with a quantity of abrasive material in the shape of small, irregularly shaped, hard iron "stars" or "picks." The barrel is rotated slowly and the falling about of the castings and the stars gradually knocks the burnt sand and scale off the surfaces of the casting. This method has the disadvantage of producing a hard skin upon the castings which causes difficulty if they are subsequently to be machined.

Rattling will never completely clean any but very simple castings, and a better method consists in pickling the castings by immersion in a dilute sulphuric or muriatic acid solution. The acid attacks the iron somewhat, thereby loosening the sand and scale. Pickling in a 15 per cent solution of sulphuric or muriatic acid requires about twelve hours and must be followed by a careful washing in water. Hydrofluoric acid now sometimes replaces sulphuric or muriatic acid. The former attacks the sand itself, instead of the iron, and with only about a 5 per cent solution castings may be cleaned in an hour or less.

The sand blast is the most convenient method of cleaning large castings, especially those of very irregular form, such as gears, etc. Very often the sand blast is followed by pickling.

The final operation in the preparation of castings for use consists in smoothing up the irregularities left by breaking off the gates, the "fin" formed where the metal has run between the two portions of a mold, etc. With small castings this is most readily done with an emery wheel. With larger castings chipping with a cold chisel is often necessary, and a pneumatic chipping tool is most efficient. Portable emery wheels fitted with a flexible drive are also used for this purpose

PROPERTIES OF CAST IRON

CONSTITUTION

166. Essential Constituents of Cast Iron. The composition of cast iron is that of a complex alloy containing usually six important elements, together with other elements of less frequent occurrence. The elements invariably present are, in the approximate order of their importance, iron, carbon, silicon, phosphorus, sulphur, and manganese. In addition, copper, nickel, oxygen and nitrogen are often present, and aluminum, titanium, and vanadium are sometimes added.

The constitution of cast iron is much more complex than the composition, because of the variety of compounds which the elements present combine to form. The most important consideration affecting the character and properties of cast iron is the carbon content and, in particular, the form assumed by the carbon, i.e., whether free as graphite, or in chemical combination with the iron as a carbide. The importance of the elements other than the iron and carbon is chiefly due to their influence upon the state assumed by the carbon.

Before the essential constituents of cast iron can be stated even in a general way the existence of three principal classes of cast iron must be recognized, the difference in character being due to the different states in which the carbon occurs.

Gray cast iron is that in which the carbon occurs chiefly in the graphite state.

White cast iron is that in which the carbon occurs chiefly as the carbide of iron.

Mottled cast iron is a mixture of particles of gray iron with particles of white iron.

Semi-steel is a trade name given to mixtures of pig iron, with from 20 to 50 per cent of steel scrap, which are melted in a furnace. The resulting metal is usually fine grained and much stronger than ordinary cast iron.

167. Carbon in Cast Iron. When cast iron solidifies from the molten state the carbon probably remains in the combined condition as carbide of iron, Fe_3C, which is partly free as cementite and partly in solid solution in the iron as "austenite." * The Fe_3C is an unstable compound, however, and when formed at a high temperature is readily decomposed into graphite and iron.

The decomposition of the carbide with the consequent formation of graphite carbon is facilitated particularly by a slow rate of cooling and by the presence of silicon. It is retarded, on the other hand, by rapid cooling or by the presence of much sulphur or manganese.

168. Gray Cast Iron. Cast irons containing considerable amounts of graphite carbon are known as gray cast irons, because of the grayish or blackish coarsely crystalline appearance of their fractures. This appearance is caused by the presence of many irregular and generally elongated and curved plates of graphite imbedded in the matrix of ferrite and cementite. These plates of graphite are made up of smaller plates, somewhat like sheets of mica, and may be split apart with ease. The individual sheets of graphite vary in size from microscopic proportions to one-eighth of a square inch or more in area. The characteristic structure of gray cast iron when highly magnified is shown in the photomicrograph of Fig. 44. The irregular dark bands are graphite plates, the intermediate area being the ferrite-cementite matrix. The actual percentage by weight of graphite in gray cast iron will be between 2 and 4 per cent, the amount of combined carbon being under $1\frac{1}{2}$ per cent. The volume content of graphite is much higher, however, since iron has a specific gravity about three and one-half times that of graphite.

FIG. 44. — Gray Cast Iron. Magnified 100 Diameters. (Boylston.)

169. White Cast Iron. Cast iron, the bulk of whose carbon is present in chemical combination with iron as carbide of iron (Fe_3C), or cementite, is called white cast iron because of the white, highly metallic fracture

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* See Art. 125 for an explanation of the term "solid solution," and Art. 128 for a definition of "Austenite."

which characterizes it. The ferrite and a portion of the cementite together form pearlite, so that the ultimate constitution of an iron free from graphite will be a mixture of cementite and pearlite. Pearlite is a mixture of cementite and ferrite, the two components occurring most commonly as small wavy or parallel plates of alternately light and dark color. The characteristic appearance of laminated pearlite under high magnification is shown in Fig. 45. Ferrite and cementite combine in rather definite proportions to form pearlite, the proportion of carbon to pure iron being 1:120. The appearance of white cast iron when highly magnified is shown in Fig. 46, wherein the light areas are free cementite, while the dark-banded areas are pearlite.

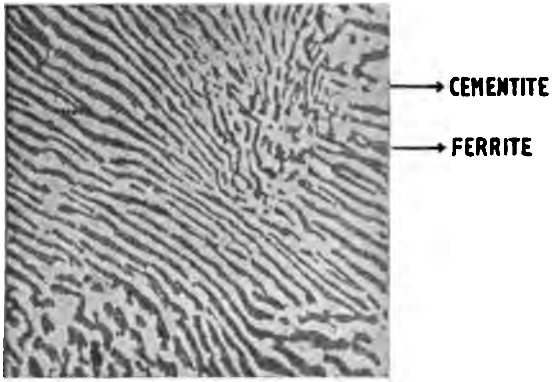

Fig. 45. — Pearlite. Magnified 1000 Diameters. (Osmond.)

While white cast iron is structurally not distinct from very high-carbon steel, if the occurrence of larger amounts of elements other than iron and carbon is disregarded, it lacks entirely the malleability of steel and is extremely hard and brittle because of the presence of a very large proportion of the hard and brittle free cementite. The dividing line between high-carbon steel and white cast iron lies at about 2.2 per cent carbon but, as a matter of fact, most steels do not approach 2 per cent carbon and few white cast irons have less than 2.25 per cent or even 2.50 per cent carbon.

Fig. 46. — White Cast Iron. Magnified 500 Diameters. (Wust.)

170. Mottled Cast Iron. Irons which contain particles of gray cast iron mixed with particles of white cast iron, which are therefore non-homogeneous in character, are sometimes produced. Such irons are called mottled cast irons. They have no special adaptation, and their production is largely unintentional.

171. Silicon in Cast Iron. After iron and carbon, silicon is, in its effects upon the character of the iron, the most important element present in cast iron. The amounts of silicon and sulphur retained in pig iron are under the control of the blast-furnace manager, and the amounts present in cast iron are similarly under the control of the foundry manager. The content of carbon and phosphorus, on the other hand, is not under control, nor is that of manganese, except to a slight extent.

Silicon combines with a part of the iron to form the silicide (Fe_2Si), which forms a solid solution with the ferrite. The primary effect of silicon upon the carbon is as a precipitant, driving the carbon out of combination into the graphite form. The maximum precipitation of graphite seems to occur with about 2.5 to 3.5 per cent of silicon.

Silicon in percentages below about 3.0 per cent acts, therefore, as a pronounced softener, producing soft gray iron, but larger percentages result in the formation of hard and brittle iron due to the excess of the hard, brittle iron silicide, Fe_2Si. Small percentages also produce freedom from oxides and blowholes, promote fluidity, and decrease shrinkage and depth of chill.

172. Sulphur in Cast Iron. The influence of sulphur upon the form assumed by the carbon in cast iron is the reverse of the influence of silicon. The higher the sulphur content, the higher will be the proportion of combined carbon. This tendency upon the part of sulphur is much more potent than is the opposite tendency exhibited by silicon, however, a given amount of sulphur being able to neutralize about fifteen times as much silicon. Sulphur therefore tends to produce hard, brittle, white iron.

Aside from the effect of sulphur upon the character and properties of iron on account of the fact that the carbon is driven into combination as the carbide, sulphur if present as iron sulphide, FeS, possesses the power to materially affect the behavior of iron in solidifying and cooling. Only a few tenths of 1 per cent of sulphur suffices to render iron very tender at a red-heat ("red-short"), and therefore apt to check or crack if in solidifying the shrinkage causes the casting to tend to crush the sand of the mold, thus resulting in the setting up of internal stresses in the iron. Sulphur also causes solidification to become very rapid, and often is responsible for the presence of blow-holes and sand-holes.

Manganese, because of its great affinity for sulphur, will tend to rob the iron sulphide, FeS, of its sulphur, forming MnS, which latter compound is much less potent than FeS in affecting the proportion of combined carbon. A given percentage of sulphur may, in general, be neutralized by the presence of about twice as much manganese. Specifications usually limit the maximum sulphur content of gray cast iron to not over 0.10 per cent and often the maximum allowance does not exceed 0.05 per cent.

173. Phosphorus in Cast Iron. Chemically, phosphorus tends to increase the proportion of combined carbon, especially when the silicon is low and the phosphorus high. On the other hand, phosphorus lengthens the time of solidification, thereby affording opportunity for the precipitation of graphite. When the silicon is high, therefore, the presence of moderate amounts of phosphorus actually increases the precipitation of graphite, but when the proportion of phosphorus is very large, the chemical effect is great enough to retain the carbon in the combined form in spite of the longer period of solidification.

The presence of phosphorus in considerable amounts tends therefore to produce a hard white iron, lacking in toughness and workability, and especially lacking in shock resistance when cold. Phosphorus reduces the melting-point of iron and makes it very fluid. It is therefore useful in making very thin castings where a less fluid iron will not take a perfect impression of the mold. Not more than 0.05 per cent of phosphorus is allowed in best gray iron, while from 1.0 to 1.5 per cent is sometimes used when fluidity is more important than toughness.

174. Manganese in Cast Iron. Manganese increases the tendency for iron to hold carbon in solution and therefore increases the proportion of combined carbon, though it is much less potent in this latter respect than is sulphur.

If no more manganese is present than is required to combine with the sulphur, forming MnS, its effect will not be to increase the proportion of combined carbon, but will be just the reverse, because the sulphur is taken from the sulphide, FeS, which is so powerful in causing the carbon to assume the combined form. Any additional manganese unites with carbon to form the carbide Mn_3C, and this carbide unites with the Fe_3C, causing the cementite to be made up in part of the double carbide of iron and manganese $(FeMn)_3C$.

It appears, therefore, that manganese up to the amount which combines with sulphur to form MnS tends to lower the proportion of combined carbon and consequently decreases the hardness and brittleness of the iron. Any additional manganese, however, has a marked effect in causing the carbon to assume the combined form, and is therefore a hardener.

BEHAVIOR OF IRON IN COOLING

175. Shrinkage. The shrinkage of cast iron is an important consideration for the pattern maker, because due allowance for shrinkage must be made in the dimensions of the pattern if the casting is to conform to the size called for by the drawings. It is also an important consideration for the designer and the founder, because the stresses set up in cooling and the consequent danger of checking are directly dependent upon the degree of shrinkage if the casting be of such a shape that its shrinkage tends to crush the sand in the mold.

All metals expand upon heating and contract when cooling, and the total expansion in melting a metal will correspond to its total shrinkage in solidifying and cooling. Pure iron shrinks about 0.3 of an inch per foot; a less pure iron usually shrinks less, because impurities, particularly carbon, usually lower the melting-point.

The separation of carbon as graphite exerts a powerful influence upon the total net shrinkage of iron because of the expansion which its separation causes.

The factors which chiefly determine the amount of shrinkage are therefore the factors which chiefly control the separation of graphite, i.e., the silicon content and the rate of cooling. Moreover, since the latter is largely dependent upon the size of the castings, the shrinkage becomes largely a function of silicon content and size. This relationship is shown graphically by Fig. 47, which is based upon experiments made by W. J. Keep. The shrinkage is shown to be inversely proportional to the per cent of silicon, and for an iron of given composition the shrinkage decreases as the size of casting increases.

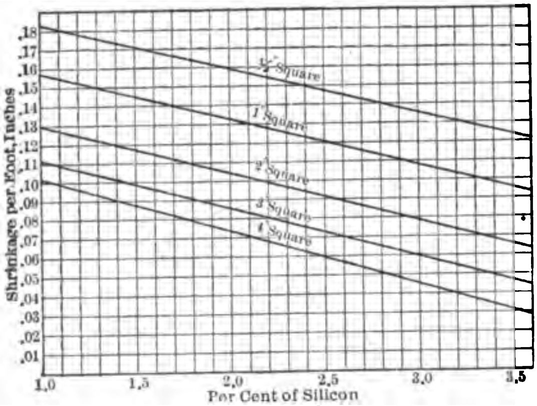

FIG. 47. — Approximate Relationship Between Shrinkage, Silicon Content, and Size.

Other elements whose presence affects the separation of graphite, either directly or by affecting the rate of cooling, naturally have an effect upon shrinkage. Sulphur, which drives carbon into combination with iron, therefore increases shrinkage unless neutralized by other elements. Phosphorus by lowering the rate of cooling tends to promote the separation of graphite and decrease the shrinkage. The separation of an iron phosphide from the solid solution near the point of solidification also causes an expansion, as is the case when graphite separates. This circumstance, therefore, increases the effectiveness of phosphorus in decreasing shrinkage.

176. Checking.* Liability upon the part of iron to check while cooling is dependent upon the magnitude of the stresses caused by the contracting of the metal upon the sand, and upon the weakness of the metal at a temperature slightly above a black heat. The factors which govern shrinkage, therefore, determine the stresses to which the cooling metal will be subjected, if the casting be of such a shape as to compress the sand in shrinking.

Sulphur is the most deleterious element affecting the strength of iron at a temperature just above a black heat. Phosphorus, by decreasing shrinkage, should decrease the liability of the metal to check, but this effect may be more than offset by the tendency of phosphorus to cause the metal to assume a coarsely crystalline structure. Manganese tends to counteract this last tendency upon the part of the phosphorus and therefore tends to prevent checking.

177. Segregation. Segregation in castings is the collecting together of impurities in spots. The primary cause of segregation is the effect of impurities in lowering the freezing-point of iron. This results in forming a fluid solution which remains molten after the remainder of the metal has solidified, and runs to that part of the casting which has the loosest texture. These spots, often called "hot spots," are apt to occur in the middle of the larger sections of the casting. They are often porous, and are usually hard and brittle.

The tendency to segregation is proportional to the amount of impurities present. Phosphorus is especially apt to cause segregation, and manganese and sulphur have the same effect to a less marked extent. Segregation is not commonly encountered in iron founding, however, since other considerations will usually require a degree of freedom from excessive amounts of phosphorus, sulphur, or manganese which will minimize the danger of segregation.

178. Chilling. The intentional chilling of iron by the insertion of metal chills in a mold has been discussed in Art. 163. The production of properly chilled iron is a very difficult problem, mainly on account of the effect of variations in composition of the iron upon the depth of chill obtained. The most important factors in this regard are the contents of silicon and of sulphur. If the silicon is comparatively high and the sulphur very low chilling is practically impossible. If both silicon and sulphur are very low a considerable amount of chill is obtained, and the best results are obtained when a low percentage of silicon is combined

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* Development of minute cracks.

with a rather high percentage of sulphur. Phosphorus has little effect upon the depth of chill. Manganese increases the hardness of the chilled iron.

PHYSICAL AND MECHANICAL PROPERTIES

179. Hardness. The precise meaning of the term hardness as applied to metals is not altogether fixed. Properly, hardness should be considered simply the measure of the resistance of the metal to being cut or scratched by a tool, or to being worn away by abrasion. Tenacity and brittleness are properties which are quite distinct from hardness, yet many methods employed for measuring hardness do not recognize any distinction.

The principal factor in determining the hardness of cast iron is the amount of combined carbon. This is due, first, to the hardness of cementite itself, and second, to the fact that increase in combined carbon usually means a decrease in graphite carbon, which is very soft. (Graphite has a further effect in increasing the ease with which cast iron may be worked, because it acts as a lubricant for the cutting tool.)

The influence of elements other than carbon upon the hardness of iron is, with the exception of manganese, directly dependent upon their power to vary the amount of combined carbon. Silicon, therefore, acts as a softener, unless its percentage exceeds about 3 per cent, when the effect is reversed. Sulphur and phosphorus act as hardeners in all percentages, and manganese, in addition to its indirect effect on combined carbon, has a direct hardening influence owing to the hardness of the compound $(FeMn)_3C$.

TENSILE STRENGTH

180. Tensile Strength in General. The tensile strength of cast iron is dependent upon so many variable factors that no general statement may be made concerning it. The founding methods, the design, and the size of castings are always important factors influencing strength. In addition, the composition and, more particularly, the constitution exert an enormous influence upon strength.

181. Influence of Form of Carbon. Gray cast iron has been represented to consist of plates of weak, soft, wholly non-metallic graphite, forming a more or less complete mesh-work which separates the ferrite and cementite matrix into partially isolated particles. The cementite and ferrite matrix of gray iron is really a low- or medium-carbon steel, possessing great toughness combined with great softness, ductility, and low strength. White cast iron, upon the other hand, is a mixture of cementite and pearlite, not distinct from high-carbon steel except in the relatively greater impurity of the white cast iron, and the higher percentage of free cementite.

The presence of graphite plates in any proportion must necessarily decrease the strength of the steel matrix and, therefore, the strength of the iron as a whole, because the graphite breaks up the continuity of the steel matrix. This injurious effect of graphite is not necessarily directly proportional to the percentage of graphite present but, rather, is proportional to the degree of continuity of the graphite mesh.

Any diminution in the proportion of graphite will, in general, however, mean a diminution in some degree of the continuity of the graphite mesh and will, therefore, mean a lessening of its detrimental effect upon strength. At the same time, a diminution in the proportion of graphite means an increase in the proportion of combined carbon or cementite in the steel matrix. This increase in the proportion of cementite in the matrix means a proportionate increase in its strength until the percentage of cementite in the iron reaches a certain point, which is in the neighborhood of 1.2 per cent for an iron containing about 4.0 total carbon. Further increases in the percentage of cementite beyond this point increase hardness and brittleness at the expense of toughness, ductility, and strength. It is, therefore, evident that the strength of an iron will be greater when the percentage of combined carbon does not exceed about 1.2 per cent than it will be if any higher percentage be present. Whether the highest strength is found with about 1.2 per cent cementite or when the percentage of cementite is below this point will depend upon whether the loss of strength due to increase in graphite, on the one hand, or the gain in strength due to the higher carburization of the steel matrix, on the other hand, is the more influential factor.

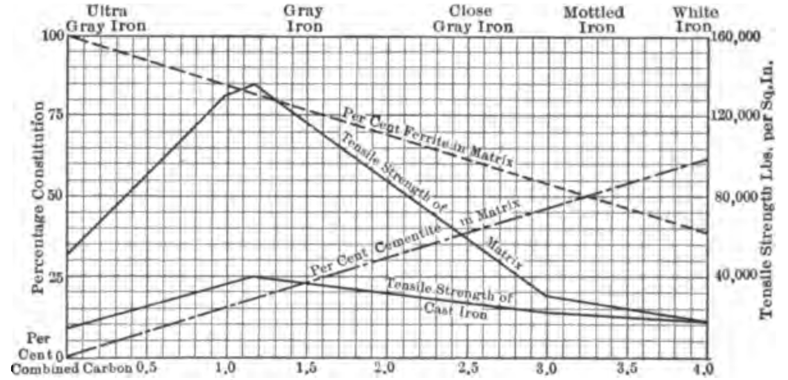

FIG. 48. — Approximate Relationship Between Tensile Strength of Cast Iron and State of Carbon. (Howe.)

The approximate relation between tensile strength and state of carbon is shown graphically by the diagram of Fig. 48, which is abstracted from the original of Professor Henry M. Howe. In this diagram it has been assumed that the iron possesses a constant total carbon content (4 per cent).

182. Influence of Metalloids and Rate of Cooling upon Strength. The influence of the metalloids and the rate of cooling upon the strength of castings is largely an indirect one, dependent upon the extent to which the separation of graphite is facilitated or retarded.

Silicon in small amounts, by favoring the precipitation of graphite, exerts an influence which is beneficial to strength, provided that an excessive amount of combined carbon would otherwise be present. In this event the gain in strength of the matrix which accompanies the relief of brittleness more than compensates for the injurious effect of the increase of graphitic carbon. If, on the other hand, the additional graphite precipitation caused by silicon produces an iron whose matrix possesses too little combined carbon, the iron is weakened both because of the lowering of the strength of the matrix and because of the weakening and softening influence of the graphite.

The influence of sulphur when present as FeS is always as a weakener of cast iron, not only because it prevents the separation of graphite chemically and by hastening solidification, but also because it promotes the inclusion of flaws (blow-holes, sand-holes, or shrinkage cracks), induces internal stresses, and causes coarse crystallization and brittleness. The harmful influence of sulphur may of course be more or less completely neutralized by much larger percentages of silicon or by the presence of about twice as much manganese.

Phosphorus usually tends to weaken cast iron. When the silicon is high, however, a moderate amount of phosphorus may, by increasing the time of solidification, promote the separation of graphite, as above explained, thereby improving strength. The presence of more than about 0.05 per cent phosphorus will, however, always be detrimental to strength.

The effect of manganese upon strength is always dependent upon the relative amounts of sulphur and manganese present. If the manganese content does not exceed twice the sulphur content, the manganese simply neutralizes the tendency of sulphur to decrease the proportion of graphite, and therefore the manganese increases strength. When the content of manganese exceeds the amount required to neutralize the sulphur, however, the excess manganese has a marked effect detrimental to strength because of the resultant excessive increase in the proportion of combined carbon.

183. Stress-strain Diagram for Cast Iron. Cast iron will exhibit a great variation in elastic properties, since so many factors affect its strength.

In Fig. 49 typical stress-strain diagrams for three radically different cast irons are presented in order to illustrate their usual behavior under tensile stress.

It will be observed that there is no well-defined elastic limit or yield point. For the typical irons shown in Fig. 49 the ultimate strength falls at 35,500 pounds per square inch for the hard gray iron, 22,500 pounds per square inch for the average gray iron, and 16,000 pounds per square inch for the soft gray iron.

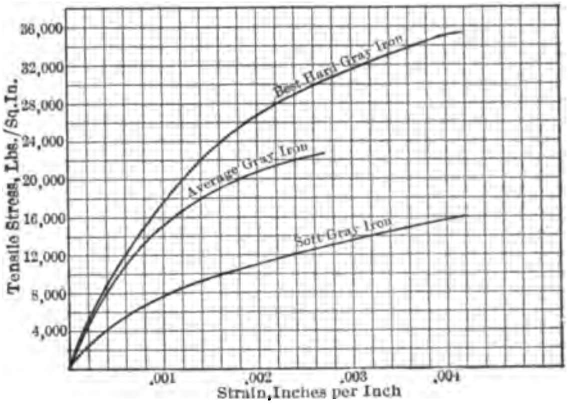

FIG. 49. — Stress-strain Diagrams for Cast Irons. (Tension.)

No constant proportionality of stress to strain exists for any considerable load interval, and therefore it cannot properly be said that cast iron has a modulus of elasticity. If we consider, however, that the term may be applied to the ratio of stress increment to corresponding strain increment for successive small load intervals, we find that the value of E is initially about 30,000,000 pounds per square inch for hard cast iron, 24,000,000 pounds per square inch for average iron, and 14,000,000 pounds per square inch for soft iron. At 5000 pounds per square inch stress, the values of E have decreased to about 20,000,000 pounds per square inch, 15,000,000 pounds per square inch, and 7,000,000 pounds per square inch, respectively; and at 10,000 pounds per square inch stress, the values of E are about 15,000,000 pounds per square inch for hard iron and about 14,000,000 pounds per square inch for average iron.

The percentage elongation is small for all cast irons, rarely exceeding from 3 to 4 per cent for any grade, and the reduction of area is usually too slight to be appreciable.

184. Specification and Allowable Stress. The specifications of the American Society for Testing Materials recognize a distinction in properties between light, medium, and heavy castings. Castings having any section less than ½ inch thick are classed as light castings; castings having no section less than 2 inches thick are classed as heavy castings; and castings not included in either of the above divisions are classed as medium castings.

The minimum ultimate tensile strength of gray iron castings should not fall below:

18,000 pounds per square inch for light castings;
21,000 pounds per square inch for medium castings;
24,000 pounds per square inch for heavy castings.

The tensile strength of semi-steel varies from 25,000 to 40,000 pounds per square inch.

COMPRESSIVE STRENGTH

185. Compressive Strength of Cast Iron. The compressive strength of cast iron, as is the case with all comparatively brittle materials, is largely a function of the shearing strength, since failure will occur along an oblique plane unless the specimen tested is sufficiently long to permit failure by lateral flexure.

The factors which control compressive strength are exactly the same factors which control tensile strength. The most important consideration is, therefore, the state assumed by the carbon, and compressive strength will be benefited by all agencies which tend to increase the proportion of graphite carbon and decrease combined carbon, until the point of saturation of carbon in the steel matrix is reached (about 1.2 per cent combined carbon), beyond which point further increases in graphite mean a loss in strength of the matrix, and therefore a loss in strength upon the part of the iron as a whole.

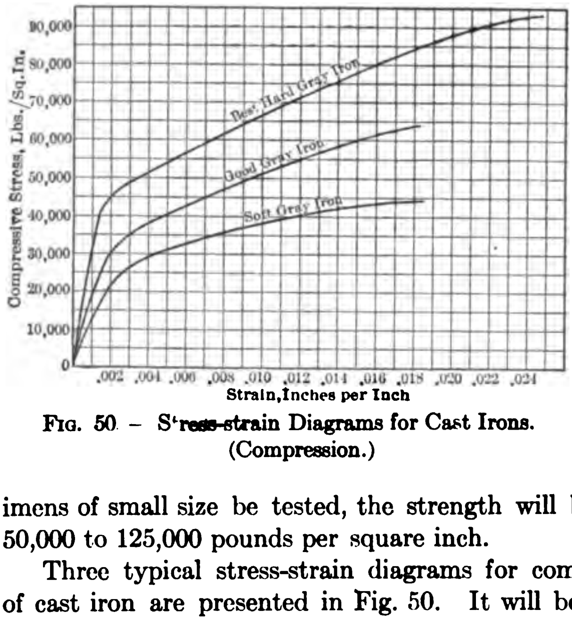

FIG. 50 – Stress-strain Diagrams for Cast Irons. (Compression.)

Compressive tests of cast iron show very wide variation in strength. If large specimens such as structural columns, etc., are tested, the ultimate strength will seldom be found to exceed 30,000 to 40,000 pounds per square inch. If, however, short specimens of small size be tested, the strength will be found to run to from 50,000 to 125,000 pounds per square inch.

Three typical stress-strain diagrams for compression of short blocks of cast iron are presented in Fig. 50. It will be observed that the yield point is much more clearly marked in compressive tests of cast iron than in tensile tests, although no absolutely constant ratio of stress to strain is maintained for any considerable load interval.

The ultimate strengths of the three irons of Fig. 50 are 93,000 pounds per square inch, 63,000 pounds per square inch, and 44,000 pounds per square inch, for hard, average, and soft irons, respectively. The moduli of elasticity at 10,000 pounds per square inch are about 30,000,000 pounds per square inch, 20,000,000 pounds per square inch, and 12,000,000 pounds per square inch, for the three classes of iron, while at 20,000 pounds per square inch stress the value of E has dropped to about 25,000,000 pounds per square inch, 16,000,000 pounds per square inch, and 8,000,000 pounds per square inch, respectively.

Cross-breaking Strength

186. Cross-breaking Strength, Modulus of Rupture. The cross-breaking strength of cast iron is very valuable as the criterion by which the quality of the material going into gray iron castings may be judged. Cross-breaking strength is closely allied to tensile strength, since bending stresses are a combination of tensile stresses on one side of the neutral axis of the beam with compressive stresses on the other. The extreme fiber stress on the tension side of the beam is naturally the controlling factor, since cast iron is so much stronger in compression than in tension, and the load which produces failure is that load which causes an extreme fiber tensile stress equal to the ultimate tensile strength of the material.

The cross-breaking strength is commonly expressed by use of the term "modulus of rupture," meaning the apparent extreme fiber stress under the load which produces rupture as computed from the rule,

$$f = My \div I,$$

wherein f is the extreme fiber stress, M is the bending moment, y is the distance from the neutral axis to the extreme fiber, and I is the moment of inertia of the section.

As a matter of mechanics, this procedure is not warranted since it involves the assumption that the neutral axis remains a constant distance from the extreme fiber, and the further assumption that a constant proportionality of strain to stress obtains for all stresses up to the breaking stress.

The proportion of strain to stress is not a constant and the neutral axis shifts as the material deforms. Therefore the actual extreme fiber stress is less than this value of f computed by the rule for the bending moment which exists under the load which produces rupture, and, indeed, the actual fiber stress is in the case of cast iron not more than 50 to 60 per cent of the modulus of rupture.

The factors influencing cross-breaking strength are the same as those influencing tensile strength, since failure under transverse loading is really failure by tension on the tension side of the beam.

In addition to these factors it has been shown that the transverse strength of cast iron is also dependent upon the size and shape of the specimens and the span upon which they are supported under load. Many series of tests have shown that specimens of small section show relatively much higher transverse strength than do specimens of large section, and are also much more sensitive to small variations in composition. Other tests have shown that round sections have a higher modulus of rupture than rectangular sections.

In view of these circumstances efforts have been made by the American Society for Testing Materials to determine the size and shape of test specimen best fitted for adoption as a standard, and also the proper span upon which the beam should be supported. Their investigations have led to the widespread adoption of the "arbitration test bar" which is circular in section, 1¼ inches in diameter, and 15 inches long. The bar is broken under a central load upon a span of 12 inches. Longer specimens of rectangular sections are used in some cases.

187. Specification and Allowable Cross-bending Stress. The American Society for Testing Materials specifies that the minimum breaking strength of the arbitration bar under transverse load (the load being applied centrally on a span of 12 inches) shall not be under:

2500 pounds for light castings;
2900 pounds for medium castings;
3300 pounds for heavy castings.

Also, "the deflection shall in no case be under 0.10 inch."

These loads on a span of 12 inches correspond to the following values of the modulus of rupture:

39,000 pounds per square inch for light castings;
45,000 pounds per square inch for medium castings;
52,000 pounds per square inch for heavy castings.

CHAPTER V

MALLEABLE CAST IRON

188. Definition of Malleable Cast Iron. Malleable cast iron is iron of special composition which, after having been cast in its final form, is rendered malleable by a process of annealing. It is essential that the iron used be a white iron before annealing, in order that the carbon may be almost wholly in the combined form. The annealing process will then result in the conversion of the combined carbon into free carbon in an amorphous condition, not resembling free carbon in the crystalline form as graphite. This amorphous carbon will exist as isolated particles in a continuous mesh of metal. The casting is through this circumstance rendered very much tougher than white or gray cast iron, and its ductility and malleability are increased to such an extent that it may be bent or twisted to a considerable degree even when cold.

189. Malleable Cast Iron as a Material of Engineering Construction. Malleable cast iron has no important applications as a purely structural material, but is largely used in the manufacture of machinery, implements, railway rolling stock, light hardware, etc.

It combines the advantages of ordinary cast iron with respect to the ease with which complicated forms may be cast, with a considerable degree of toughness, ductility, and strength. Only cast steel or steel forgings can compete with malleable iron for the uses above noted.

MANUFACTURE OF MALLEABLE CASTINGS

190. The Materials Used. The charge of the furnace of a malleable-iron foundry includes pig iron, sprues, annealed malleable-iron scrap, and steel scrap.

The pig iron should contain not more than 0.60 per cent manganese, not more than 0.225 per cent phosphorus, and not more than 0.05 per cent sulphur; total carbon need not be specified. The silicon requirement varies according to the castings made. Heavy castings require from 0.75 to 1.50 per cent silicon, while light castings require from 1.26 to 2.00 per cent.

The sprues or "hard scrap" include the gates and scrap castings that have not been annealed. Thorough cleaning of the sprues to remove the burnt sand is very necessary.

Malleable scrap is difficult to melt because of the comparative infusibility of the skin of malleable castings. It contributes greatly to the strength of the castings made, however, and if the large scrap is broken up before charging, it may be handled without serious difficulty.

Steel scrap of any sort may be used as a part of the charge with beneficial results, if added after the balance of the bath is molten.

191. The Furnace. Three types of furnaces are principally used in melting iron for malleable casting: the cupola, the air furnace, and the open-hearth furnace. The cupola furnace has been described in Art. 149 and the air furnace in Art. 150. The open-hearth furnace used in the malleable-iron foundry differs in no essential respect from the open-hearth steel furnace except in size, the capacity of the open-hearth furnace used in the malleable-iron industry being usually from 10 to 20 tons.

192. Melting Malleable-iron Mixtures. The cupola process for melting iron for malleable-iron castings differs in no respect from ordinary gray-iron foundry practice, except in the higher proportion of fuel charged. The advantages of the cupola process lie in the cheapness of installation and operation, the comparative ease with which the furnace is controlled, and the small loss of silicon in melting. The disadvantages are the extreme liability of burning, owing to the direct contact of metal and fuel, and the extremely close structure of the hard castings produced, which causes trouble in annealing. Very little malleable scrap, and no steel, can be used in the cupola. Cupola iron requires an annealing temperature about 150° C. (302° F.) higher than does iron melted in the air furnace or open-hearth.

The advantages of the air furnace as compared with the cupola are principally the better grade of castings produced, the wider range of scrap material used, the shorter time required for pouring, the less serious consequences of a breakdown, and the better control over process and product. The disadvantages of the air-furnace process are the greater expense of equipment, the greater skill required in operation, and the longer time required in melting.

The open-hearth furnace is operated in the malleable-iron foundry in almost exactly the same manner as in the production of open-hearth steel. Its advantages over the air furnace are the saving of time required for melting, the very exact control of the process, and the resultant high efficiency and gain in the percentage of first-grade castings. The disadvantages are the high cost of installation, the heavy repair bill, the necessity of having gas fuel, and the necessity of continuous operation.

193. Molding Methods for Malleable Castings. Molds for malleable castings are made in the same manner as gray-iron castings in green sand.

Particular care must be exercised to provide proper gating in handling white-iron mixtures, and risers or feeders must be provided where thin sections are encountered to prevent cooling of the metal at these points before the mold is completely filled.

Chills are very commonly used in molds for malleable castings, particularly for the sake of cooling the larger parts of castings rapidly, thereby preventing the possibility of graphite separating out, as it tends to do with slow cooling.

194. Pouring the Castings. Molten white iron is a very different material from molten gray iron. The former must be poured very hot, and as rapidly as possible, to insure proper complete filling of the mold. Iron which has chilled slightly, or which has been burned in the furnace, will be sluggish, and must not be poured except in pig-beds for use in subsequent heats.

195. Subsequent Treatment of the Castings. Hard castings for malleable iron are cleaned by any of the methods common to the gray-iron foundry.

Very careful inspection of the cleaned castings is necessary, and all defective castings are rejected before being annealed. The gates are also chipped off and the castings are separated into a number of classes.

196. The Annealing Process. The annealing process consists in heating the castings to a red heat and maintaining them at that temperature for a sufficient time to change practically all of the carbon from the combined form to the free amorphous form called "temper" carbon. In order to prevent oxidation at this temperature, and also warping of the castings, the latter must be packed in annealing pots surrounded by a proper packing material.

This packing material might be sand, clay, or other inert material and the heat alone would effect the desired change in the state of the carbon and produce malleable castings. Higher grade and stronger castings are produced, however, when the packing material is a decarbonizing agent such as iron oxide. This results in the migration of carbon from the outer shell of the casting, producing a layer resembling steel about $\frac{1}{16}$ inch thick, encased in a skin of almost carbonless iron on the surface. This skin may subsequently be enriched in carbon by a case-hardening process, and if the reduction of carbon has previously been carried to the maximum depth possible (about $\frac{1}{4}$ inch), the resultant material will greatly resemble cast steel It may even be hardened and tempered.

The annealing pots are usually three or four cast-iron boxes, without bottoms, stacked one above another, and placed on a "stool" which supports them above the floor of the furnace. The usual size of the annealing pots does not exceed 18 by 24 inches, 15 inches high, but pots of specially large size or of special form are sometimes required.

The packing material used is commonly the cinder or slag squeezed from the wrought-iron puddle balls. This slag is a very rich iron oxide high in silica. Hematite ore in a pulverized state is also used as a packing material, especially for cupola iron whose annealing temperature is sufficient to cause puddle cinder to cake together and fuse onto the castings. Rolling-mill scale is also used, and magnetite has been found very satisfactory. If sand has not been perfectly removed from the castings, it causes trouble by combining with the oxide of the packing material, increasing its fusibility and causing the castings and packing to bake together.

The annealing oven or furnace is built in many quite different forms, the principal factors being the type of fuel used and the mechanical equipment of the plant. In general, the oven usually utilizes the down-draft principle and, since the castings must cool slowly in the furnace itself, it cannot be continuous in operation, and does not employ the regenerative principle. Fig. 51 illustrates one common type of annealing oven employing gas fuel. The flames are deflected downward from a vaulted roof, pass between the pots, and escape through floor openings to flues beneath leading to the stack. A damper in the stack flue is depended upon to control the draft. Large ovens are provided with gas burners at either end.

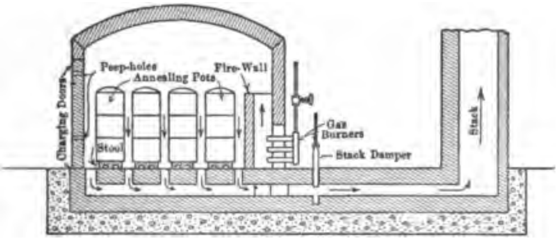

Fig. 51. — Annealing Oven for Malleable Cast Iron.

When coal fuel is used the gas burners are replaced by grates, a firing door, and an ash pit.

Ovens are usually built in batteries of from six to twelve, adjacent ovens having common side walls. When overhead cranes are used for charging and discharging, the roof arches may be built in such a way that they may be removed in sections by the charging crane.

Two standard annealing processes are in use, depending upon the class of malleable iron produced. "Black-heart" malleable iron is usually produced in American practice, while "white-heart" malleable iron is usually produced in European foundries. The latter process requires a higher annealing temperature, which is maintained for a much longer time.

Most annealing ovens will attain the required temperature of about 750° C. (1382° F.) in from 24 to 36 hours. The annealing temperature is maintained for a period of about 60 hours in the case of black-heart castings, and about 100 hours for white-heart castings. In the black-heart process but little of the temper carbon is removed, as is shown by the fracture, wherein only a very narrow band of gray material encloses the velvety black interior. The white-heart process is seldom applied to metal more than ½ inch thick, and the removal of carbon is carried to the ultimate degree possible, the decarburization being effected to a depth of as much as $\frac{3}{16}$ or even ¼ inch.

The cooling of the castings after annealing should be as slow as possible. Usually from fifty to sixty hours are permitted before the pots are withdrawn from the oven. The entire annealing process therefore requires from four to six days.

197. Treatment of Annealed Castings. The annealed castings must be cleaned to remove the scale which has formed. This is accomplished in tumbling barrels.

In order to test the quality of the annealed iron, "test-plugs," which are simply small projections, about ¾ by ½ by 1 inch long, are cast on the more important work. These are broken off and the fracture examined. If normal, the fracture should have a black velvety surface in the interior, surrounded by a band of dark gray about $\frac{1}{16}$ inch thick, and this in turn is encased in a band of white not more than $\frac{1}{64}$ inch thick.

PROPERTIES AND USES OF MALLEABLE IRON CASTINGS

198. Chemical Composition and Constitution. The proper composition of good malleable iron is indicated by the following analysis:

	PER CENT
Silicon	0.45–1.00
Manganese	about 0.30
Phosphorus	not more than 0.225
Sulphur	not more than 0.06
Total carbon (before annealing)	at least 2.75

The constitution of malleable iron is extremely variable, even in a single casting, because the effect of the annealing process is largely dependent upon the thickness of the casting. The outermost skin is practically carbonless iron (ferrite). The intermediate gray portion of black-heart malleable consists largely of ferrite, but contains scattered particles of free carbon in the amorphous state called temper carbon. The black interior consists of ferrite in which many isolated particles of temper carbon are interspersed. White-heart malleable castings have the constitution of the intermediate portion of black-heart castings for the most part, but the outermost band of practically pure ferrite is much thicker in the case of the former than in the case of the latter.

199. Physical Properties. Tensile Strength and Ductility. The tensile strength of malleable castings is much more important than the tensile strength of ordinary gray-iron castings, and the tensile test is a better indication of the quality of malleable iron, because the ductility of the material allows it to be evenly gripped in the jaws of the testing machine without danger of introduction of cross-bending stresses.

Tensile tests of malleable iron should be made on bars 12 inches long and ⅝ inch diameter for 4 inches in the middle. Elongation is measured over a 2-inch gauged length, the fracture being included in this length. The strength of black-heart malleable castings should not be less than 28,000 pounds per square inch. The elongation in 2 inches should not be less than 5 per cent.

200. Transverse Strength. The transverse test of malleable iron is important because it is an indication of ductility and toughness as well as transverse strength. The transverse strength may be determined by supporting a 1-inch square bar on a span of 12 inches and applying a central concentrated load. Observations of deflection under the breaking load are made. The usual breaking load for such specimens is not less than 3000 pounds, with a deflection of ½ inch, and for specially well-made malleable castings the breaking load may amount to as much as 5000 pounds, with a deflection of 1½ inches. (The above loads correspond to moduli of rupture of 54,000 pounds per square inch, and 90,000 pounds per square inch, respectively.) The A. S. T. M. standard specimen is 14 inches long, 1 inch wide and either ½, ⅝ or ¾ inch in thickness. The center load on a 12-inch span and the deflection are specified.

201. Uses of Malleable Castings. The uses for which malleable castings are especially adapted are very numerous. This material is especially useful in the manufacture of that large class of articles whose form is too complicated for economical forging, but which must possess a strength and toughness not attainable in gray castings.

Among the more common applications of malleable iron may be especially mentioned its use on railroad work. Couplers are commonly made of malleable iron, as are the journal boxes, brake fittings, and many other small fittings for rolling stock. Other uses include many agricultural implements and parts of agricultural machinery, all manner of pipe fittings, elbows, unions, valves, etc., household and harness hardware such as parts of locks, hinges, window and door fittings, buckles, swivels, etc.

Another class of articles are made of malleable iron which has been case-hardened after prolonged annealing. The material then closely resembles cast steel, and is often sold as such. This class of articles includes many carpenter tools, such as hammers, hatchets, chisels, planer irons, etc., also pistol parts, skates, shears, etc.

CHAPTER VI

THE SPECIAL ALLOY STEELS

202. Definition and Classification of Alloy Steels. The Committee on Uniform Nomenclature of Iron and Steel of the International Association for Testing Materials defines *alloy steel* as "steel which owes its distinctive properties chiefly to some element or elements other than carbon, or jointly to such other element and carbon." *Ternary alloys*, or three-part alloys, are those whose properties are chiefly dependent upon the presence of one element other than iron and carbon. *Quaternary alloys* contain two influential elements other than iron and carbon.

All alloy steels bear names which indicate the nature of the alloying element present. The principal classes of alloy steels are those listed below:

Ternary Alloys

- Nickel steel
- Manganese steel
- Chrome steel
- Tungsten steel
- Molybdenum steel
- Silicon steel
- Vanadium steel

Quaternary Alloys

- Nickel-chromium steel
- Chromium-manganese steel
- Tungsten-chromium steel
- Nickel-manganese steel
- Nickel-vanadium steel
- Nickel-tungsten steel
- Nickel-silicon steel
- Tungsten-manganese steel
- Manganese-silicon steel

203. Nickel Steel. Nickel steel usually contains between 2 and 5 per cent of nickel with from 0.10 to 0.50 per cent of carbon. This class of alloy steel combines great tensile strength and hardness, with a high elastic ratio, good ductility and relatively high resistance to corrosion. Certain special nickel steels are remarkable for their low coefficient of temperature expansion, such as that containing 36 per cent nickel (Invar steel) whose coefficient approaches zero and that containing 42 per cent nickel (Platinite) which at ordinary temperatures has about the same coefficient as glass.

Critical Ranges. The presence of nickel in varying amounts has an important effect upon the position of the critical points in cooling. Three and eight-tenths per cent nickel lowers the critical points about 75° C. (167° F.), and as the nickel is increased this effect becomes more pronounced until with about 25 per cent of nickel the critical range is below ordinary atmospheric temperature. This effect of nickel makes it possible to have a steel which, without quenching, may be pearlitic, martinsitic or austenitic, dependent upon the nickel-carbon ratio. Fig. 52.

Tensile Properties. The general effect of a small amount of nickel upon the tensile properties of steel is to raise the ultimate strength and elastic limit without sacrificing ductility. The characteristic properties of a given nickel steel are not dependent, solely, upon the amount of nickel, however, as the carbon content and the heat treatment are also very important factors.

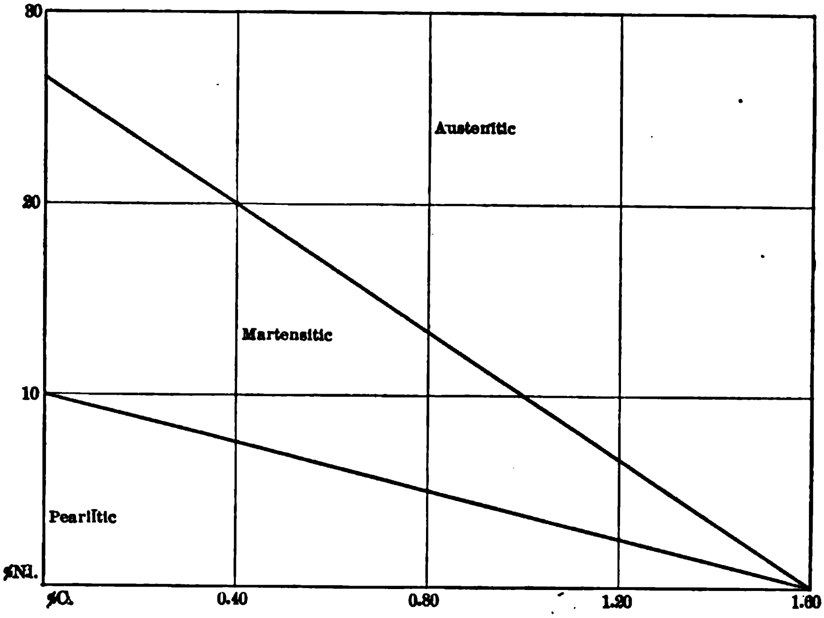

FIG. 52. — Influence of the Nickel-carbon Content upon the Structure of Nickel Steel as Cast. (Bullens.)

The comparative physical properties of nickel steels with 0.25 per cent carbon are shown by Fig. 53.

In steels with less than 5 per cent nickel the tensile strength is raised, approximately, 5000 pounds per square inch for each 1 per cent of nickel.

Magnetic Properties. Steels containing more than 24 per cent of nickel are practically non-magnetic.

Resistance to Corrosion. Low nickel steels corrode less than the carbon steels under any condition of exposure. High nickel steels are used where special resistance to corrosion is required.

Uses of Nickel Steel. Nickel steels containing from 2 to 4 per cent of nickel are used for structural purposes, forgings, machine parts, steel rolls, etc. Nickel steel of this grade should always be heat treated if possible.

When the nickel content exceeds 5 per cent the metal becomes hard and cannot be worked easily, hot or cold. The hardness increases as the per cent of nickel increases. The steel containing 13 per cent nickel and 0.55 per cent carbon discovered by Arnold and Read is so hard that it cannot be machined.

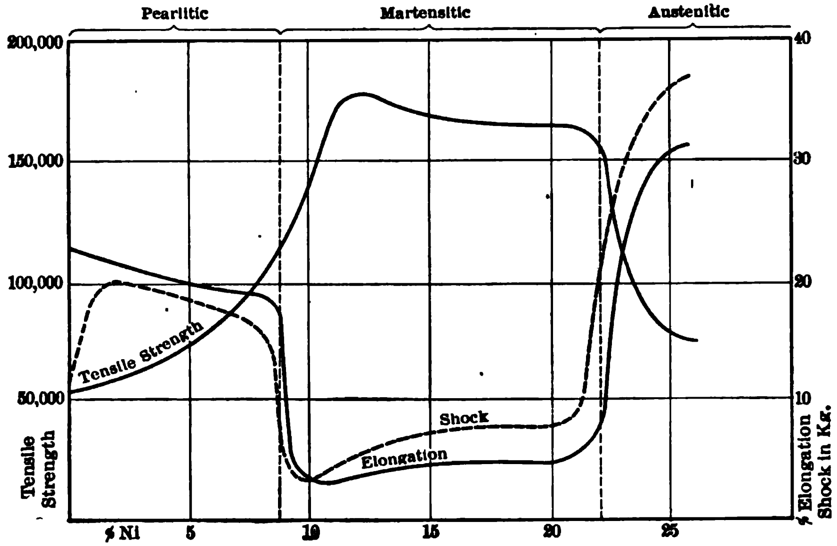

FIG. 53. — Comparative Physical Properties of Nickel Steels with 0.25 per cent Carbon. (Bullens.)

Nickel steels containing 22 to 25 per cent of nickel are used where exposure to corrosion is very severe such as parts of pumps, salt water connections, and spark plugs. Invar steel and platinite have been mentioned above.

Manufacture. Nickel steel is usually made by the open-hearth process, but may be made by any of the steel making processes. Nickel is added in the form of metallic nickel, or ferro-nickel, charged with the rest of the stock.

204. Manganese Steel. Manganese steel usually contains from 11 to 14 per cent manganese and from 0.8 to about 1.5 per cent carbon. Manganese steel was introduced by Sir Robert A. Hadfield in England in 1887–1888, and has ever since held a unique position among alloy steels. When cast in the ingot manganese steel is almost as brittle as glass, and is so hard that no carbon steel will cut it. Reheating to about 1000° C. (1832° F.), followed by quenching in water, has the remarkable effect of rendering the material very much tougher and very much more ductile without materially altering its hardness. No treatment will materially soften manganese steel when cold, and it must therefore be usually cast to as nearly its final form as possible and subsequently be finished by grinding. Manganese steel is very fluid when molten, and sound castings are produced. The shrinkage is excessive, however (often more than $\frac{3}{8}$ inch per foot). The metal may be worked or forged with great difficulty through a short range of temperatures above a red heat. It is practically non-magnetic under all circumstances unless it has long been maintained at about 500° C. (932° F.). Its habit of elongation after the yield-point is passed in tension differs from that of carbon steel in that it does not neck down, but its elongation and contraction of area are quite uniformly distributed over the entire length of the specimen.

Structure and Constitution. The presence of manganese in the amount normally used in manganese steels has been shown to be responsible for the complete suppression of the allotropic changes which normally occur in the heating or cooling of carbon steels. Sir Robert Hadfield has shown that the heating and the cooling curves of cast and forged manganese steels containing from about 10.9 to about 13.4 per cent manganese do not show the slightest retardations at any point between −200° C. (−392° F.) and +1355° C. (2471° F.). Manganese steel has no critical points. (One exception to the above statement must be made in view of the fact that Sir Robert Hadfield has been able to develop critical points in the neighborhood of about 750° C. (1382° F.), by prolonged heating at about 500° C. (932° F.). The steel so treated became slightly magnetic.)

Tensile Properties. The remarkable properties of manganese steel are illustrated by the diagrams of Fig. 54 which exhibit the tensile properties of steels containing from 0.84 to 21.69 per cent manganese. Steels which have been tested as rolled, others which have been forged, but not otherwise treated, and still others which have been quenched in water from a white heat are included in the series of test results presented. These diagrams constitute a summary of the tests of manganese steels published by the discoverer of the valuable properties of this alloy steel.

The following facts appear to be established by Hadfield's tests:

As the manganese content of steel is raised above 1 per cent the carbon content tends to increase, the proportionate increase of carbon with respect to manganese gradually becoming greater with higher manganese steels.

The tensile strength of rolled manganese steel which has not been subjected to any heat treatment increases only very slightly with increase in manganese and, in fact, does not nearly equal the strength which might be expected to characterize a carbon steel of the same carbon content. Moreover, the increase of manganese rapidly reduces the ductility, and no rolled manganese steel containing more than about 2.5 per cent manganese shows more than about 5 per cent elongation in a gauged length of 8 inches.

The tensile strength of manganese steel which has been forged, but not otherwise heat-treated, increases fairly rapidly with increase in manganese between 7 and 19 per cent, but is very low for the 7-per-cent-manganese steel and never equals that of an ordinary steel of the same carbon content. The ductility of these steels is of a very low order, although they may be forged with care. The elongation is never in excess of about 5 per cent.

The tensile strength of water-quenched steels containing in excess of 7 per cent manganese mounts rapidly with increase in manganese until

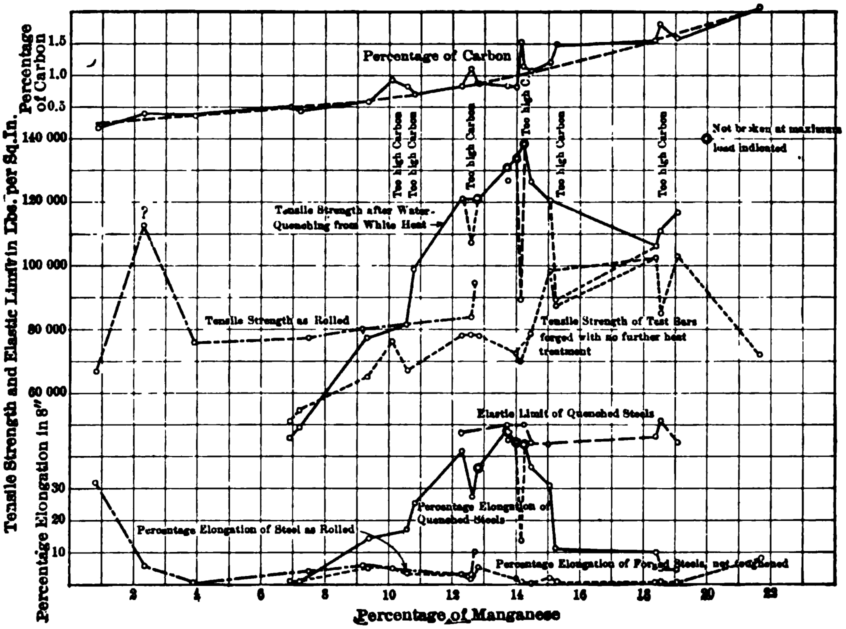

Fig. 54. — Tensile Properties of Manganese Steels. (Hadfield.)

a maximum of more than 140,000 pounds per square inch is reached with about 13 or 14 per cent manganese. With still higher manganese content the strength rapidly falls off again.

More important than the tensile strength of the quenched steels, however, is the wonderful ductility developed. With only 7 per cent manganese the elongation is only about 1.5 per cent, but it rapidly increases with increase in manganese until a maximum elongation exceeding 50 per cent is reached when the manganese content is about 13 or 14 per cent. Further increases in manganese rapidly decrease ductility. The ductility and the tensile strength remain practically directly proportional for all percentages of manganese.

A comparison of the elongation of the quenched steel and the forged steel containing about 13 or 14 per cent manganese reveals the fact that the elongation has been raised by quenching from about 1 or 2 per cent to more than 50 per cent. At the same time the strength has been increased about 100 per cent, and the hardness has not been materially impaired. Some of these bars were bent cold, after testing, nearly 180°. In no case was there any sign of necking down, but the contraction of area and distribution of elongation were nearly uniform over the entire length of the reduced section of the test bars.

The elastic limit, as determined by the "first permanent set" is very low in proportion to the tensile strength. For the steels containing from 13 to 15 per cent manganese the stress at the elastic limit amounted to only 35 to 40 per cent of the tensile strength, being about 50,000 pounds per square inch for the steels whose tensile strength exceeded 140,000 pounds per square inch.

There are certain noticeable irregularities in these curves, certain test bars appearing to show abnormal properties. On account of the possibility that these anomalies might be explained by an abnormal carbon content, the amount of carbon in each steel has been indicated by the uppermost curve on the diagram, and what seems to be the normal carbon content is indicated by the dotted curve. A comparison between the carbon curve and the various strength and elongation curves now becomes very interesting. It would seem that practically every anomalous test result may be accounted for by an abnormal carbon content.

Manufacture and Uses. Manganese steel is made by the open-hearth process whenever large masses are required. It may be made in the crucible, however. Manganese is added to the steel in the form of ferromanganese just before the completion of the process.

Large quantities of manganese steel are used as steel castings, particularly where great hardness and strength combined with great toughness are called for. It finds a special application in the construction of those parts of crushing and grinding machinery which are subjected to severe shock and abrasion. It is also used for curve rails, frogs, and crossings where hardness and freedom from brittleness constitute a great advantage, and to a limited extent for axles and treads of wheels of railway rolling stock. Its principal limitation in machine construction is the practical impossibility of machining it to final form by ordinary methods, on account of its excessive hardness.

205. Chrome Steel. Chrome steel usually contains from 1.5 to 2 or 2.5 per cent chromium together with from 0.7 to 1.5 or even 2.0 per cent carbon. Its value is due principally to its property of combining intense hardness after quenching with very high strength and extremely high elastic limit. It is therefore especially well able to withstand abrasion, cutting, or shock. The quenching treatment does not improve its ductility, as is the case with manganese steels, but on the other hand it is more ductile than a similarly treated carbon steel of the same carbon content.

Structure and Constitution. Thermal Critical Points. The characteristic structure of chrome steels containing less than about 5 or 6 per cent chromium does not differ materially from that of carbon steels similarly treated except for the presence of emulsified or finely granulated chromium carbide. With more than about 6 per cent chromium the structure of annealed steel "consists of chromiferous ferrite containing particles of double or triple (chromium) carbides, the carbide masses varying in size, some being very minute specks, and others of considerable dimensions."

Chrome steels possess distinct critical temperatures corresponding to those of ordinary carbon steels.

Tensile Properties. The tensile properties of a series of steels containing from 0.62 to 32.46 per cent chromium are exhibited by the diagrams of Fig. 55. The steel from which the test specimens were cut, was heated three hours at 850° C. (1562° F.), prior to testing. The tests were made by M. Albert M. Portevin.

For the most part the iron-chromium carbon alloys represented by the diagram of Fig. 55 do not represent the particular alloys which are important as alloys steels. Only one or two facts illustrated by the diagram will therefore be noted.

All of the steels containing between 1 and about 20 per cent of chromium show remarkably high tensile strengths, only one steel in this series showing less than 170,000 pounds per square inch.

The elastic limit of most of these steels is remarkably high in proportion to the tensile strength.

The ductility as indicated by the contraction of area is rather low for all of the steels except those containing in excess of about 20 per cent chromium.

The tensile properties of all of the steels are closely dependent upon the carbon content, most of the anomalies in the various curves being directly attributable to an abnormal carbon content.

The steels whose tensile properties are indicated by the curves of Fig. 56 more nearly represent the chrome steels which are commercially used. The tests upon which these curves are based constitute a portion of the very detailed study of the physical properties of 2 per cent chrome steels made by Professor Andrew McWilliam and Mr. Ernest J. Barnes. The relation between tensile properties, carbon content, and heat treatment of 2 per cent chrome steels is well shown by these tests.

The following general statements cover the most important facts established by this series of tests of 2 per cent chrome steels:

The tensile properties of chrome steels, whether heat-treated in any manner or not, are dependent upon the carbon content to a very marked degree.

In general the tensile strength and yield-point increase rapidly, and the ductility decreases as the carbon content increases. The maximum beneficial effect of carbon would seem in most cases to be attained when the carbon content does not greatly exceed 0.7 or 0.8 per cent. (An exception to this statement must be made in the case of steels which have been neither hardened and tempered nor annealed.)

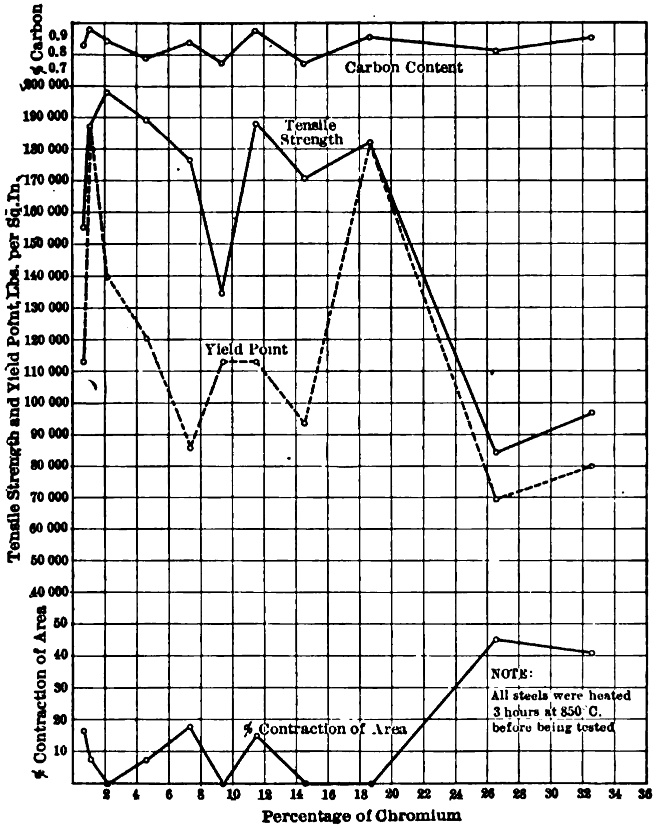

FIG. 55. — Tensile Properties of Various Chrome Steels. (Portevin.)

The yield-point of 2 per cent chrome steels is remarkably close to the tensile strength in case the steel has been quenched and tempered. With moderate tempering the yield-point may exceed 95 per cent of the tensile strength.

The tensile properties of chrome steels which have not been heat-treated (hardened and tempered) do not excel those of ordinary steel of similar carbon content in any way except that they are slightly more ductile.

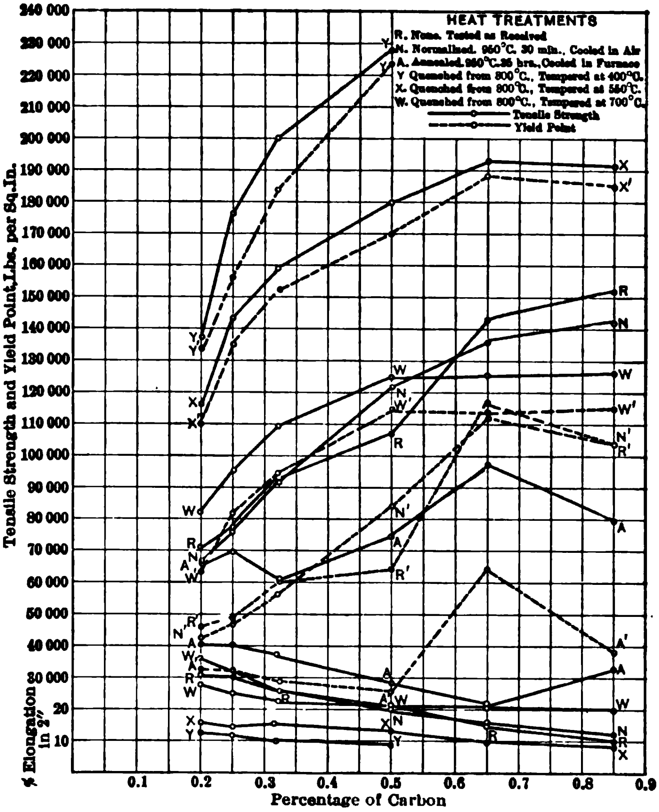

FIG. 56. — Relation of Tensile Properties of 2-per-cent-Chromium Steels to Carbon Content and Heat Treatment. (McWilliam and Barnes.)

The tensile strength is about doubled, the yield-point about tripled, and the ductility reduced about one-half, by quenching from 800° C. (1472° F.), followed by tempering at 400° C. (752° F.). Tempering at higher heats reduces the strength and yield-point and increases the ductility in proportion to the tempering heat employed.

Quenching followed by moderate tempering raises the tensile strength of 0.2 per cent carbon steel from 67,000 to 137,000 pounds per square inch, and the yield-point from 42,000 to 134,000 pounds per square inch. When the carbon content is 0.5 per cent, this same treatment raises the tensile strength from 122,000 to 228,000 pounds per square inch, and the yield-point from 84,000 to 224,000 pounds per square inch.

By drastic annealing at high heats, long prolonged, the tensile strength is very much reduced and the yield-point is lowered even more in proportion, while the ductility is very notably increased.

When it is recalled that the possession of this tremendous strength, and a yield-point unapproached by any other steel (except nickel-chromium steel), is combined with a hardness almost equal to that of manganese steel, the commercial value of this class of steel may be appreciated. It is rather lacking in ductility, but this is often unimportant in view of its extremely high elastic limit.

Corrodibility. All chrome steels corrode less rapidly than ordinary carbon steel, but the advantage is far less marked in the case of the 1 per cent chrome steel than it is in the case of a 5.3 per cent chrome steel.

The superiority of chrome steels is most marked when the exposure consists in allowing the steel to be alternately wet and dry. The advantage conferred by the addition of the chromium is somewhat less marked on exposure to weak acids, sea water, or tap water, but is still considerable, and especially so in the case of 5.3 per cent chrome steel.

Manufacture and Uses. Chrome steel is made in the crucible or in the open-hearth furnace. Chromium is added in the form of ferro-chrome, and since the latter oxidizes easily, the loss will be very heavy in the open hearth unless it is added just before the end of the process.

Chrome steel is used where a hard surface and shock resistance are desired. It is commonly used in the manufacture of projectiles and (in a quaternary alloy with nickel) armor plate. It is also used for a limited class of tools and dies, for gears and other parts of automobiles and machines generally, for the wearing parts of rock-crushing machinery, and for safes and vaults. In the latter application of chrome steel it is welded with alternate layers of wrought iron into a composite three- or five-ply plate. The chrome steel resists cutting by drills, while the wrought iron introduces an element of toughness so that it is better able to withstand concussion.

206. Tungsten Steel. Tungsten has long been recognized to be a most valuable alloy element for special steels. It is, however, most commonly used in conjunction with chromium or manganese in a quaternary alloy, instead of being used with carbon alone as a ternary alloy. The ternary alloys of iron, tungsten, and carbon possess a certain amount of commercial importance, however.

Tungsten steel usually contains from 3 to 10 per cent of tungsten and from 0.2 to 1.0 or even 2.0 per cent carbon. The tensile properties of tungsten steel resemble those of high-carbon steel, the strength and especially the elastic limit being high, but the ductility low. After moderately rapid cooling from high temperatures, however, the tungsten steels exhibits remarkable hardness which is still retained upon heating to temperatures considerably above the ordinary tempering heats of carbon steels. It is this property of tungsten which makes it a valuable alloy for use (in conjunction with chromium or manganese), in making of the so-called "high-speed" tool steels.

The tungsten steel which contains about 4 or 5 per cent of tungsten and 0.5 to 0.7 per cent carbon possesses remarkable magnetic reluctance. It is a valuable material therefore for use in constructing permanent magnets, since when once magnetized, it will retain magnetism much longer than ordinary iron or steels.

Tensile Properties. The tensile properties of two series of steels containing from 0.4 to 27.05 per cent tungsten, together with about 0.2 per cent carbon, and about 0.8 per cent carbon, respectively, are exhibited by the diagrams of Fig. 57. This diagram is based upon a series of tests made by Portevin. It will be noted that for both series of steels the tensile strength and elastic limit increase with increase in tungsten until a maximum strength is reached with 10 per cent tungsten, and 12 per cent tungsten, in the respective cases of the high- and low-carbon steels. The ductility is also reduced with increase

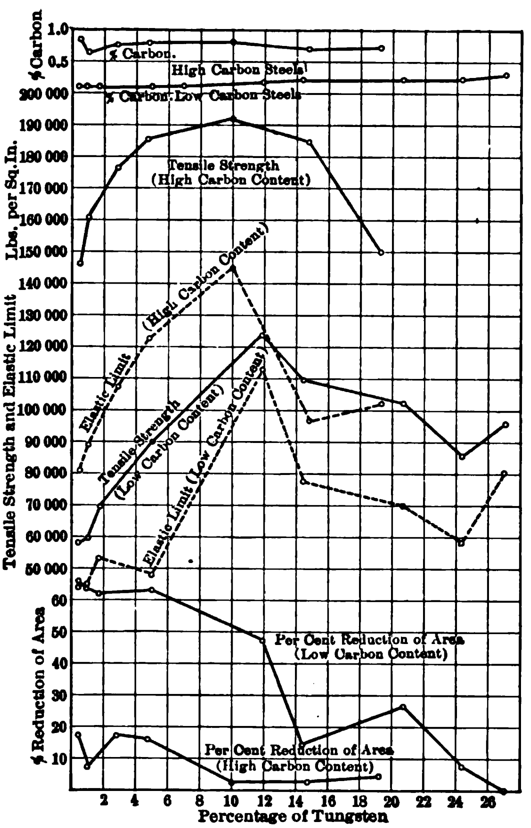

FIG. 57. — Tensile Properties of Tungsten Steels. (Portevin.)

in tungsten. (These steels have been heated three hours at 850° C. (1562° F.), prior to testing.)

The marked difference in the properties of a high- and a low-carbon tungsten steel is shown by a comparison of the curves of Fig. 57.

Manufacture and Uses. Tungsten steel is made almost exclusively by the crucible process, the tungsten being added in the form of ferro-tungsten, as wolframite, or, less commonly, as metallic tungsten.

Tungsten steel is used for few purposes other than for machine tools. These must be forged roughly to form and finished by grinding. The great advantage of this steel over ordinary high-carbon tool steel is its ability to hold its hardness at high temperatures, thus making it possible to run machines at high speed with heavy cuts. It is excelled in this respect, however, by the special steels classed as "high-speed" tool steels, which contain chromium or manganese in addition to tungsten. The uses of tungsten steel as a magnetic steel has been mentioned.

207. Molybdenum Steel. The action of molybdenum in steels is generally accepted to be similar in character to that of tungsten in so far

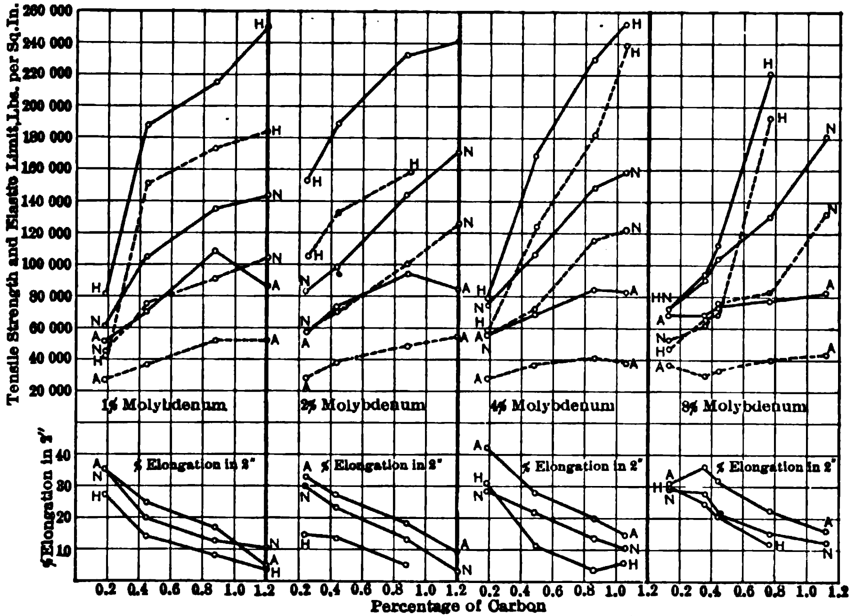

FIG. 58. — Tensile Properties of Molybdenum Steels. (Swinden.)

Tensile Strength——————————o——————————

Elastic Limit..............................o..............................

N. Normalized, 15 min. at 900° C. (1652° F.), Air cooled.

A. Annealed, 5 hrs., at 950° C. (1742° F.), Cooled in Furnace.

H. Hardened and Tempered, Quenched at 950° C. (1742° F.) to 800° C. (1472° F.) in Oil.

as the influence of the alloy upon critical temperatures, hardening power, physical properties, etc., are concerned, but the effect of molybdenum differs in magnitude from that of tungsten, 1 per cent of molybdenum being apparently equivalent to 2 or 3 per cent of tungsten.

Most molybdenum steels are really quaternary alloys, since chromium or manganese is usually present in notable amounts. The best molybdenum ternary alloy steels contain from 1 to 2 or 3 per cent molybdenum and not more than 2 per cent carbon. The general physical characteristics of molybdenum steels are identical with those of tungsten steel.

Tensile Properties. The tensile properties of a series of molybdenum steels containing from 1.0 to 8.0 per cent molybdenum and 0.2 to 1.2 per cent carbon are exhibited by the curves of Fig. 58. These tests constitute a portion of Swinden's study of molybdenum steels.

The diagram is self explanatory and it will not be necessary to discuss it beyond the point of simply calling attention to the fact that with a given molybdenum content the strength and elastic limit are increased and the ductility decreased rapidly as the carbon content is raised. Quenching from a temperature of from 800° C. (1472° F.) to 900° C. (1652° F.) is very beneficial to tensile properties with the exception of ductility.

Manufacture and Uses. Molybdenum steels are made in the crucible in the same manner as tungsten steels, and have practically the same uses.

208. Silicon Steel. Silicon steels resemble nickel steels in their general properties, but have not been used as extensively as a material of engineering construction. When 1 or 2 per cent of silicon is combined with from 0.1 to 0.4 per cent of carbon the resultant steel is one which may be classed as a high-strength structural steel resembling nickel structural steel. It is chiefly valuable because its elastic limit is very high, compared with that of an ordinary steel of equal carbon content. It is rather hard, however, and gives some difficulty in rolling.

The most valuable silicon steel is the one which is made particularly for use in electrical machinery and which was developed by Hadfield and patented in this country in 1907. Hadfield's silicon steel contains about 3 per cent of silicon and the smallest possible amounts of carbon, manganese, and other impurities. This steel acquires its remarkable magnetic properties (very high permeability and low core loss) only after a special heat treatment. It is heated to between 900° C. (1652° F.) and 1100° C. (2012° F.), cooled quickly to atmospheric temperatures, reheated to between 700° C. (1292° F.) and 850° C. (1562° F.), and cooled very slowly. Sometimes it is again heated and cooled very slowly from about 800° C. (1472° F.).

Tensile Properties. The tensile properties of a series of very low-carbon silicon steels are exhibited by Fig. 59. These curves are based upon tests made by Mr. Thomas Baker. These steels do not excel ordinary medium high-carbon steels in tensile strength nor ductility,.but do

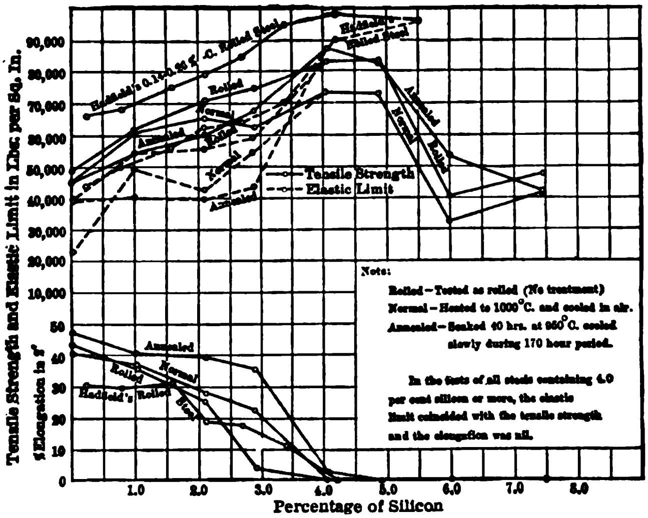

FIG. 59. — Tensile Properties of Steels Containing 0.04 per cent Carbon. (Baker.)

show a very high elastic ratio. In the presence of so small an amount of carbon, the addition of silicon seems to be beneficial to strength only in amounts not exceeding about 5 per cent, and all of these steels acquire great brittleness if about 2.0 per cent silicon is exceeded.

Similar tests made by Hadfield at an earlier date with steels containing about the same range of silicon content, but having from 0.14 to 0.26 per cent carbon (Fig. 59), exhibit about the same properties as the very low-carbon steels used by Baker, except that the strength and elastic limit is slightly higher. Hadfield found forging of his steels impossible when the silicon content exceeded 5.5 per cent.

Manufacture and Uses. Silicon steel may be made in the crucible, but is more often made in the open hearth. The alloy element is added in the form of ferro-silicon. A small amount of silicon steel has been used as a hard, high-strength, structural steel for purposes similar to those above noted in discussing nickel steel. The principal commercial application of this alloy, however, is as thin sheet steel for the construction of the cores, pole pieces, etc., of electrical machinery.

209. Vanadium Steels. Vanadium is, with the single exception of carbon, the most powerful element for alloying with iron yet discovered. Only 0.1 to 0.15 per cent of vanadium raises the tensile strength and elastic limit of low- or medium-carbon steel 50 per cent or more without any sacrifice of ductility. With high-carbon content (about 0.8 per cent carbon), and about 0.2 per cent vanadium, the tensile strength is about equal to that of an ordinary steel of corresponding carbon content, but the elastic limit is very much higher and the steel is much more ductile than a similar carbon steel.

Little more than 0.2 per cent vanadium seems to be advantageous in any steel, and amounts exceeding about 0.3 per cent are very detrimental to strength.

Vanadium steels may be forged or rolled with only minor special precautions; they respond readily to heat treatments; are enormously strong when hardened by quenching and moderately tempered; and are very tough, and stand impact, vibration, or reversal of stress very well.

Vanadium has an important quieting influence upon molten steel when cast in the ingot, and therefore promotes soundness by preventing the occlusion of gases.

The use of vanadium in steels designed for a great variety of purposes is becoming more common every year, and, in addition to the ternary alloys of vanadium carbon and iron, vanadium is used in a variety of quaternary alloy steels in which chromium, nickel, etc., are also present.

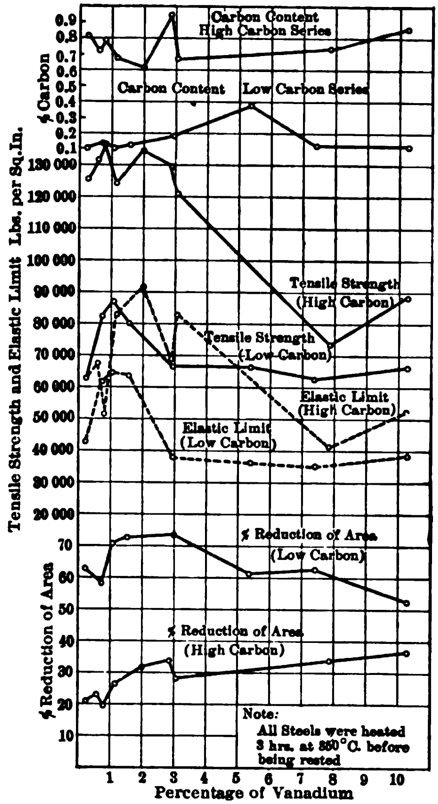

FIG. 60. — Tensile Properties of Various Vanadium Steels. (Portevin.)

Structure and Constitution. The structure and constitution of vanadium steels, either normal or heat-treated, do not differ from those of corresponding carbon steels. The vanadium appears to exist for the most part as a carbide, but a small amount is usually also present in the free ferrite. The thermal critical points seem not to be markedly affected by the small amount of vanadium used. The beneficial effect of vanadium upon the strength and ductility of steels cannot be definitely explained, but is probably due partly to its beneficial effect upon the behavior of the molten metal above noted. The formation of carbide and the presence of vanadium in the ferrite may also constitute advantageous factors.

Tensile Properties. The tensile properties of two series of steels containing about 0.2 per cent, and about 0.8 per cent carbon, respectively, are shown by Fig. 60. The tests represented by this diagram constitute a portion of Portevin's study of ternary alloys referred to above.

The beneficial effect of from 0.1 to 0.3 per cent vanadium upon tensile strength and, more particularly, the elastic limit, is plainly shown by these tests. The remarkable ductility of these steels, as indicated by the percentage of reduction of area, is also worthy of special note.

Vanadium steels are very responsive to heat treatments, the effect of the hardening treatment followed by moderate tempering being especially remarkable because of the extent to which the yield-point and, less notably, the tensile strength is raised.

Manufacture and Uses. Vanadium steels were originally made in the crucible, but are now commonly made in large masses in the open hearth. The vanadium is added in the form of ferro-vanadium, introduced after the recarburizer has been added when the conditions of the process are reducing, rather than oxidizing, in order to avoid loss by oxidation.

Vanadium steel is used to a considerable extent for castings and forgings for machines, automobiles, and railway rolling stock. It is also used for axles, springs, shafting, and gears, and a structural grade of vanadium steel has recently been introduced, the material being rolled to the ordinary structural shapes, and used in the construction of long-span bridges and other structures subjected to severe conditions of service.

QUATERNARY ALLOYS

210. The Quaternary Alloys. Many of the quaternary alloy steels are no less important commercially than the ternary alloys discussed above. The quaternary alloys have not been as systematically studied as have most of the ternary alloys, and no effort will therefore be made to consider separately the properties of each one in detail.

On account of the number of variable factors involved, the properties of the quaternary alloys cannot conveniently be represented by curves. For this reason the following tables are inserted which summarize the results of tests made by Dr. Guillet.

The tensile specimens used were round bars, 13.8 millimeters in diameter, and 100 millimeters between gauge points (½ inch by 4 inches, nearly). All specimens marked "normal" had been normalized by heating at 900° C. (1652° F.), followed by slow cooling. The "quenched" specimens were quenched in water from 850° C. (1562° F.), except certain of the tungsten-chromium steels whose special treatment is noted.

PROPERTIES OF QUATERNARY ALLOYS

NICKEL-TUNGSTEN STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4".	Brinell hardness.	
C.	Ni.	W.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.2	6.0	0.3	78,100	227,400	63,700	21.0	146	387
	5.0	0.3	96,700	226,000	78,800	17.0	179	418
	6.0	0.7	90,900	....	81,000	16.0	192	444
		2.0	105,300	220,500	81,000	14.0	207	387
		6.0	125,400	177,700	90,700	16.0	226	302
0.4	3.0	0.3	93,500	....	66,800	13.5	196	321
	4.0	0.7	88,400	....	64,700	15.5	174	555
	4.0	2.0	105,300	....	89,500	13.0	207	477
	4.0	5.0	108,800	....	85,700	14.0	217	495

NICKEL-VANADIUM STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4".	Brinell hardness.	
C.	Ni.	Va.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.2	6.0	0.1	86,700	218,900	69,700	24.5	166	302
		0.3	108,100	223,200	81,800	18.0	192	293
		0.5	103,100	204,700	82,700	19.0	235	321
		0.7	119,400	226,700	93,100	15.5	235	321
0.4	3.5	0.1	96,400	....	69,700	21.0	179	402
	3.0	0.3	98,300	....	73,900	20.0	196	460
	3.5	0.5	103,800	183,500	81,000	19.0	183	460
	3.0	0.7	109,500	....	79,900	16.0	166	375

NICKEL-MANGANESE STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4″.	Brinell hardness.	
C.	Ni.	Mn.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.15	2.0	5.0	201,300	....	140,800	6.0	311	340
		7.0	....	218,700	....	....	364	444
		15.0	99,800	....	41,700	7.0	187	187
	12.0	5.0	152,800	122,800	58,600	15.5	212	223
		7.0	87,800	89,300	50,200	36.5	146	131
		15.0	93,400	....	65,400	35.5	170	118
	30.0	5.0	100,400	92,000	38,400	30.0	149	126
		7.0	102,700	83,600	38,400	22.0	124	107
0.75	2.0	5.0	....	107,000	....	....	277	255
		7.0	105,000	91,400	62,000	3.0	235	223
		15.0	114,200	116,000	70,500	18.0	212	183
	12.0	5.0	143,400	....	59,200	11.5	174	153
	30.0	5.0	132,600	104,800	36,300	32.0	174	153
		7.0	123,600	102,700	38,400	30.0	196	137

CHROMIUM-MANGANESE STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4″.	Brinell hardness.	
C.	Mn.	Cr.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.2	3.0	3.0	136,300	168,600	89,800	5.0	293	364
		5.0	174,200	154,300	174,200	0.0	444	418
	10.0	3.0	126,000	155,400	68,900	4.0	248	444
		5.0	108,300	117,200	33,400	29.0	196	234
	15.0	3.0	125,700	122,800	40,100	19.5	114	105
0.8	2.0	3.0	136,000	153,300	119,800	8.0	364	477
		5.0	118,700	138,700	92,500	10.0	302	418
	12.0	3.0	101,600	97,400	50,100	25.0	183	159
		5.0	122,600	105,700	58,700	14.0	217	179

NICKEL-CHROMIUM STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4″.	Brinell hardness.	
C.	Ni.	Cr.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.20	5.0	3.0	143,800	203,400	117,800	10.0	248	444
		10.0	162,100	241,800	98,100	8.0	402	418
	12.0	3.0	236,000	276,700	236,000	6.0	430	475
		10.0	174,800	....	93,800	14.0	277	332
		20.0	130,800	129,300	110,600	20.0	225	217
	30.0	3.0	98,100	91,700	69,700	26.0	121	137
		10.0	128,700	125,600	97,900	10.0	143	196
0.80	5.0	3.0	21,750	....	21,750	1.5	255	402
		10.0	204,700	....	20,480	2.0	555	512
	12.0	3.0	174,100	209,000	113,100	29.5	311	302
		10.0	118,000	130,800	56,800	33.5	286	196
0.30	2.5	0.5	77,800	....	60,600	24.4	137	418
		1.0	78,200	176,000	57,200	23.0	146	430
		2.0	98,300	190,500	65,100	20.0	166	430
		3.0	197,600	230,300	197,600	0.0	275	444
		5.0	230,400	266,000	191,900	4.5	248	444
0.20	6.0	0.5	108,100	203,400	64,700	18.0	183	277
		1.0	170,500	228,700	146,500	12.0	286	460
		2.0	223,300	201,900	174,800	7.0	375	418
		5.0	238,800	187,700	193,300	6.0	402	387
		6.0	155,000	214,600	155,000	0.0	460	402

MANGANESE-SILICON STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4″.	Brinell hardness.	
C.	Mn.	Si.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.2	2.0	0.5	70,600	93,100	40,600	17.5	107	234
		0.7	79,300	151,900	57,900	15.5	107	248
		1.5	85,600	164,200	65,900	14.0	153	269
	15.0	1.0	112,500	100,100	33,200	10.0	212	196
		2.0	134,300	153,100	70,600	5.0	248	300
0.5	0.5	1.0	109,000	....	71,500	12.0	248	
		2.0	118,300	....	77,100	10.0	293	
	12.0	0.5	103,000	....	68,600	19.0	196	
		1.0	107,700	....	65,900	15.0	202	
		2.0	103,400	....	69,800	10.0	202	

NICKEL-SILICON STEELS

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4″.	Brinell hardness.	
C.	Ni.	Si.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.2	2.0	0.5	72,600	239,500	51,000	20.5	124	418
		1.0	84,700	196,300	50,700	16.0	126	351
		1.5	104,500	183,500	73,100	19.0	179	351
		2.0	114,300	179,000	74,200	13.0	163	430
		5.0	137,900	162,800	108,700	16.0	235	277
	6.0	0.5	85,000	219,000	69,700	23.5	170	340
		0.8	103,800	209,000	59,700	23.0	170	321
		1.0	110,900	....	78,200	19.0	163	304
		2.0	166,300	....	125,200	11.0	248	444
		5.0	96,700	142,900	96,700	0.0	286	556
	12.0	0.5	200,500	196,300	200,500	1.0	351	387
		1.0	204,300	165,300	204,300	0.0	375	444
		2.0	241,500	288,500	241,500	9.0	375	375
		3.0	167,300	230,700	167,300	0.0	402	460
		5.0	202,600	153,600	202,600	2.0	430	418
		7.0	225,900	173,000	225,900	0.0	460	387
	30.0	2.0	88,000	85,400	34,700	36.0	143	140
		5.0	94,100	94,100	30,700	40.0	159	143
0.4	3.0	0.5	93,200	....	64,700	20.0	170	477
		1.0	124,400	....	80,200	12.5	174	
		1.5	112,900	....	87,000	6.5	202	477
		2.0	138,700	....	101,700	14.0	228	
		3.0	152,200	....	120,800	2.5	262	555
		7.0	....	....	....	....	286	
0.8	2.0	2.0	180,000	....	100,200	8.0	293	495
		5.0	119,100	....	98,100	9.5	351	512
	12.0	2.0	147,100	....	147,100	0.0	153	364
	15.0	1.0	118,000	....	118,000	0.0	143	332
		2.0	120,800	....	120,800	0.0	179	364
		3.0	240,300	....	240,300	0.0	196	364
	20.0	1.0	133,700	98,100	32,700	33.0	143	116
		3.0	170,600	103,800	38,400	27.0	134	166

TUNGSTEN-CHROMIUM STEELS

(Quenched steels heated to 850° C. (1562° F.))

Approx. composition.			Tensile strength, lbs. per sq. in.		Elas. limit, lbs. per sq. in.	Elongation, per cent in 4".	Brinell hardness	
C.	Cr.	W.	Normal.	Quenched.	Normal.	Normal.	Normal.	Quenched.
0.2	2.0	2.0	77,800	140,800	39,700	17.0	126	261
		15.0	96,100	92,100	36,100	10.0	153	170
	3.0	13.0	91,000	....	47,800	15.6	166	163
	10.0	2.0	243,700	186,800	210,000	4.5	477	375
		15.0	122,800	115,300	47,100	10.5	196	225
	20.0	2.0	71,600	103,200	36,800	20.0	179	166
0.4	3.0	13.0	130,900	219,000	58,300	10.0	223	351
0.5	1.0	13.0	116,600	....	82,200	....	228	430
	3.0	5.0	103,900	....	64,000	16.5	166	364
		8.0	127,300	....	93,100	9.0	217	430
		13.0	124,800	....	72,500	11.5	217	364
		20.0	91,400	128,000	75,400	7.0	156	196
	8.0	13.0	127,300	150,900	106,100	6.0	228	321
0.6	3.0	13 0	130,500	197,700	67,300	12.0	228	364
0.7	3.0	13.0	136,000	....	82,200	10.0	288	314
0.8	2.0	2.0	179,100	....	143,800	4.5	518	555
		15.0	222,000	....	199,000	0.0	652	?
	3.0	13.0	122,200	183,600	90,100	15.0	217	430
	10.0	2.0	204,800	....	179,100	3.0	253	?
	20.0	2.0	127,400	114,200	53,600	10.0	207	192
		15.0	112,300	115,100	65,400	18.0	179	179

TUNGSTEN-CHROMIUM STEELS

Effect of various heat treatments on hardness

Approx. composition.			Treatment.	Brinell hardness.
C.	Cr.	W.		
0.2	3.0	13.0	Quenched at 1200° C. (2192° F.), in water	228
0.4	3.0	13.0	Quenched at 1200° C. (2192° F.), in water	495
0.5	1.0	13.0	Quenched at 1200° C. (2192° F.), in water	460
	3.0	5.0	Quenched at 1200° C. (2192° F.), in water	Cracked
		8.0	Quenched at 1200° C. (2192° F.), in water	418
		13.0	Quenched at 1200° C. (2192° F.), in water	532
		13.0	Quenched at 1200° C. (2192° F.), in water	Cracked
		20.0	Quenched at 1200° C. (2192° F.), in water	302
	8.0	13.0	Quenched at 1200° C. (2192° F.), in water	512
0.6	3.0	13.0	Quenched at 1200° C. (2192° F.), in water	Cracked
0.7	3.0	13.0	Quenched at 1200° C. (2192° F.), in water	Cracked
0.8	3.0	13.0	Quenched at 1200° C. (2192° F.), in water	532
0.5	3.0	13.0	Quenched at 1200° C. (2192° F.), after heating 1 min.	532
			Quenched at 1200° C. (2192° F.), after heating 5 mins.	555
			Quenched at 1200° C. (2192° F.), after heating 10mins.	600
			Quenched at 1200° C. (2192° F.), after heating 15mins.	600
			Quenched at 1200° C. (2192° F.), after heating 20mins.	600
			Quenched at 900° C. (1652° F.), after heating 1 min.	364
			Quenched at 900° C. (1652° F.), after heating 5 mins.	477
			Quenched at 900° C. (1652° F.), after heating 10 mins.	555
			Quenched at 900° C. (1652° F.), after heating 15 mins.	600
			Quenched at 900° C. (1652° F.), after heating 30 mins.	600
			Quenched at 1200° C. (2192° F.), in air after heating 5 mins.	600
			Quenched at 1200° C. (2192° F.), in current of air 5 mins.	600
			Quenched at 1200° C. (2192° F.), in oil 5 mins.	578
			Quenched at 1200° C. (2192° F.), in water at 15° C. (59° F.), 5 mins.	555
			Quenched at 1200° C. (2192° F.), in large volume of mercury	555

SECTION 6

THE NON-FERROUS METALS AND ALLOYS

CHAPTER I

THE PURE METALS

1. The Non-ferrous Metals of Industrial Importance. The non-ferrous metals of greatest industrial importance comprise: copper, aluminum, zinc, lead, tin, and nickel. Those of secondary importance include bismuth, antimony, cadmium, mercury and the precious metals — silver, gold, and platinum. A number of these latter metals are chiefly important as alloy elements, and many others such as magnesium, chromium, cobalt, vanadium, tungsten, molybdenum, titanium, etc., have almost no industrial applications except as alloy elements.

The non-ferrous alloys of greatest importance are the alloys of copper with tin (the bronzes), and alloys of copper with zinc (the brasses) and the alloys of aluminium. Many important special bronzes and brasses are made, however, in which a third alloy element has been included. For this purpose tin or zinc, lead, phosphorus, manganese, aluminum silicon, iron, titanium and vanadium are most commonly used.

Aside from the bronzes and brasses, copper forms more or less valuable alloys with practically all of the metals above listed; aluminum is the principal metal of a number of other important alloys, and the same thing is true of zinc, lead, tin, nickel and a few others.

The principal non-ferrous metals and alloys are listed in the classification which follows:

CLASSIFICATION OF NON-FERROUS METALS AND ALLOYS

NON-FERROUS METALS

Metals of Primary Importance
- Copper
- Aluminum
- Zinc
- Lead
- Tin
- Nickel

Metals of Secondary Importance
- Bismuth
- Antimony
- Cadmium
- Mercury
- Silver
- Gold
- Platinum

NON-FERROUS METALS (continued)

Metals Chiefly Important as Alloy Elements

- Magnesium
- Chromium
- Cobalt
- Vanadium
- Tungsten
- Molybdenum
- Titanium

NON-FERROUS ALLOYS

Ordinary Bronzes. Copper-tin Alloys.

Special Bronzes. Copper-tin	Zinc Lead Phosphorus Manganese Silicon Aluminum Vanadium Nickel Titanium	Alloys.

Ordinary Brasses. Copper-zinc Alloys.

Special Brasses. Copper-zinc	Lead Aluminum Manganese Iron Vanadium Phosphorus Silicon	Alloys.
Other Binary Alloys of Copper. Copper	Aluminum Manganese Phosphorus Silicon Vanadium Chromium Tungsten Antimony Bismuth Lead Arsenic	Alloys.
Alloys of Zinc. Zinc	Lead Tin Antimony Bismuth	Alloys.
Alloys of Lead. Lead	Tin Antimony Bismuth Cadmium Arsenic	Alloys.
Alloys of Tin. Tin	Cadmium Antimony Bismuth Nickel Zinc-lead	Alloys.

Alloys of Aluminum. Aluminum................	Copper Copper-magnesium Magnesium Zinc Copper-zinc Copper-manganese Nickel Tin Manganese Tungsten Chromium Titanium	Alloys.
Alloys of Nickel. Nickel-Copper-Zinc Alloys.		
Special Bearing Metals.........................	Bronzes (Ordinary and Special) Copper-lead Lead-antimony Tin-copper-antimony Lead-tin-antimony Lead-copper-antimony Zinc-tin-antimony Lead-tin-bismuth Lead-barium Lead-calcium	Alloys.

Space cannot be devoted to a detailed consideration of all of the metals and alloys above listed. A brief treatment of the metallurgy, properties and uses of the more important metals and alloys will be presented, supplemented by a few general statements concerning the less important ones.

COPPER

2. Classification of Commercial Forms of Copper. Copper is, with the exception of iron, the most useful and valuable metal found in nature. Its ores are found in every important country of the world, and native copper is found in the region abutting upon the south shore of Lake Superior, and in a few other localities. Copper ores exist in a great variety of forms, usually as sulphide or oxide. The greater proportion of the world's supply of copper is derived from copper pyrites.

The classification of copper most commonly used in the United States is not a particularly rational one, but is one which trade conditions have imposed. The American Society for Testing Materials recognizes three general classes of American copper, which may be defined as follows:

Electrolytic copper is copper derived by the electrolysis of a copper sulphate solution with anodes of crude copper and cathodes of pure copper. (Copper migrates from the anode, leaving its impurities behind, and is deposited on the cathode.)

Lake copper is copper which has originated on the northern peninsula of Michigan, U. S. A.

Casting copper is more or less impure copper which is either (*a*) fire-refined copper from virgin sources; (*b*) copper electrolytically produced by deposition from impure liquors, or (*c*) copper reclaimed from secondary sources.

Electrolytic copper has in recent years largely replaced all other classes of copper for all uses demanding a pure grade of copper. A large proportion of the electrolytic copper produced is derived from copper pyrites and has previously been smelted and fire-refined. The process of electrolysis results in the recovery of practically all the precious metals commonly present in copper ores, and since this gain, as well as the added market value of electrolytically refined copper, will usually pay the extra cost of electrolytic refining, the amount of casting copper produced is in consequence relatively very small. A considerable portion of even the lake copper is electrolytically refined, either to free it from impurities or to recover the silver content.

3. Ores of Copper. The most important ores of copper are the following:

Native copper occurs in large quantities on the south shore of Lake Superior in the upper peninsula of Michigan. It is also found in New Mexico, in Chili, and in South Australia.

Copper pyrites or *chalcopyrite* ($CuFeS_2$), is the ore from which the greater proportion of the world's copper supply is derived. It contains when pure, 34.4 per cent of copper, often contains both silver and gold, and is generally associated with iron pyrites.

Chalcocite or *copper glance* (Cu_2S) contains 79.89 per cent copper.

Bornite or *erubescite* (Cu_3FeS_3) contains on the average 55.6 per cent of copper. It generally occurs intermixed with chalcopyrite and chalcocite, and is doubtless a decomposition product, as is shown by its variable content of copper, ranging between 42 and 70 per cent.

Cuprite (Cu_2O) contains 88.8 per cent of copper. *Tile ore* is an intimate mixture of cuprite and limonite. Cuprite is a decomposition product of sulphur compounds of copper.

Melaconite or *black copper* contains 79.8 per cent of copper, but usually occurs contaminated with oxides of iron and manganese. Like cuprite, it is a decomposition product of sulphides.

Malachite ($CuCO_3$, $Cu(OH)_2$) contains 57.33 per cent of copper and is another decomposition product of sulphides.

Azurite or *chessylite* ($2CuCO_3$, $Cu(OH)_2$) contains 55.16 per cent of copper and is another decomposition product of the sulphides. It generally occurs with malachite.

Chalcanthite or *copper vitriol* ($CuSO_4 + 5H_2O$) is a crystalline decomposition product containing 25.4 per cent of copper, or is found in solution in the waters of mines that are working on mixtures of sulphide ores and iron pyrites, etc.

Atacamite ($CuCl_2 + 3Cu(OH)_2$) contains 59.4 per cent of copper

Chrysocolla is a hydrated silicate of copper containing an average of 39.9 per cent of copper. It is a decomposition product of sulphides and is generally associated with malachite.

Covellite or *indigo copper* (CuS) contains 66.0 per cent of copper.

Bournonite ($PbCuSbS_3$), Enargite ($[4CuS + Cu_2S]As_2S_3$), and Fahlore or Tetrahedrite ($4[Cu_2S, FeS, ZnS, Ag_2S, Hg_2S]Sb_2S_3, As_2S_3$) are ores of rare occurrence and little commercial importance.

4. The Extraction of Copper from its Ores. The metallurgy of copper is very complex on account of the great variety of ores used and the frequent necessity of providing for the recovery of not only copper, but also the precious metals which occur in copper ores. The number of metallurgical methods of extraction of metallic copper is therefore very large.

The chief sources of copper are ores which are essentially more or less complex sulphides, ores which, although originally sulphides, have by atmospheric agencies been altered to oxides and carbonates, and native copper ores wherein the copper exists as free metal.

Sulphide ores are usually treated by one of three general processes which will be briefly considered under the heads: (*A*) Roasting, smelting, and converting, (*B*) pyrite smelting, and (*C*) alternate oxidation and reduction. When the ores are wholly oxidized the copper may be recovered by a process of direct reduction.

With only minor exceptions, all of the products from the foregoing processes must be further subjected to a refining treatment before being marketed. Only two general methods of refining possess any present importance. These are (1) electrolytic refining, and (2) fire or furnace refining. The former is now the method most commonly applied.

Aside from the above-mentioned methods of derivation of copper, which may all be characterized as *dry methods*, *wet* or *chemical methods*, depending upon the getting of the copper into aqueous solution by means of suitable solvents and subsequently recovering it from the solution by electrolysis or by the use of suitable precipitants, have attained a position of commercial importance.

In the following paragraphs the several processes of derivation of copper above mentioned will be briefly considered.

Roasting, Smelting and Converting. Roasting has for its principal objects the burning of the sulphur contents of the ore to sulphur dioxide (SO_2), which passes away as gas, and the changing of the metal with which the sulphur was combined into an oxide. No effort is made, however, to eliminate entirely the sulphur, or completely oxidize the metal, since some sulphur and lower oxides are desirable in the subsequent smelting operation.

Two methods of roasting which have been practiced for generations are *heap roasting* and *stall roasting*. Heaps are built up on a bed of fuel in such a manner that the coarser lumps are in the center of the pile, while the smaller ore, in continually diminishing sizes, forms the exterior. The heap is covered with a layer of fines or concentrates. The fuel is cordwood, brushwood, heather, or coal, and passages are provided in the bed for draft.

Stall roasting resembles heap roasting except that the heaps are enclosed within low masonry walls on three sides. Stacks are usually provided to increase the draft, the top of the pile being made air-tight by a layer of fines, or a cover provided for the entire stall. In stall roasting the time is considerably shorter than with heap roasting, and a smaller proportion of the ore is insufficiently roasted.

Roasting in reverberatory furnaces similar to the furnaces used for smelting has been practiced for many years. The ore must be comparatively finely divided and this may mean an additional expense for crushing and grinding if this has not been previously required for purposes of mechanical concentration. Nevertheless, a considerable saving in time and fuel is effected by the use of the reverberatory roasting furnace in preference to the older methods of roasting out of doors in heaps or stalls.

A modern type of roasting furnace, is a shelf furnace containing six circular hearths one above the other. The hearths are provided with openings alternately at the center and at the periphery to permit of the descent of the ores. A vertical hollow shaft traverses the center of the furnace carrying rabbles which are set to move the material toward the outlet opening of each hearth. The air required for combustion is forced in by a fan at the bottom, and the products of combustion (principally sulphur dioxide gas), escape through a flue provided at the top. The ore to be roasted is delivered by hoppers to a drying hearth on the top of the furnace; rabbles gradually transfer it to the peripheral opening leading to the top roasting hearth, and by the motion of successive sets of rabbles it is gradually dropped from hearth to hearth, falling alternately at the center and the periphery, until it leaves the lowest hearth in a roasted condition. A temporary firebox must be used to heat a cold furnace to the required temperature, after which raw ore is charged and firing kept up until calcination has commenced and the ores have reached a dull red heat. Calcination thereafter continues by the combustion of the sulphur of the ore without any extraneous fuel.

Smelting of copper ores has for its object simply the concentration of the ore by removal of the earthy portion or gangue, in order that only the metallic portion may have to be treated by the subsequent more expensive refining process. It is not possible with sulphide ores to derive metallic copper as metallic iron is derived in the blast furnace, because, though the smelting operation is similarly conducted as a reducing process, the copper did not originally exist as an oxide. Iron pyrites and other sulphide minerals are not rejected but, upon melting, join the metallic portion of the material in the furnace. It is only because some portion at least of the undesirable metallic minerals have by the preliminary process of roasting been changed into the oxidized condition that their removal in the slag is in any degree possible.

The ultimate product of the smelting operation is therefore a large amount of worthless slag, made up principally of silica combined with ferrous oxide, alumina, and lime from the flux, and a small metallic portion called *matte,* which is essentially a mixture of metallic sulphides of copper, iron, and other metals originally present in the ore.

The smelting of copper ores is accomplished in one of two general types of furnace, viz., the *blast furnace* and the *reverberatory furnace.* The two methods of smelting will be briefly considered.

A copper blast furnace has two crucibles located near the ends of a shaft. Sets of tuyères penetrate the side walls of the shaft. The bottom of the shaft slopes in each direction from the center, so that the molten metal flows into the crucibles. The crucibles are provided at their front ends with slag spouts which are trapped so that the outlet is considerably higher than the opening through the crucible wall. Slag flows continuously, and the blowing of the blast out through the slag spout is prevented by the head of slag maintained above the slag outlet by the trap. At the opposite end of the crucibles tap holes are provided which allow a continuous stream of metal to flow into large forehearths.

The mechanical operation of the furnace involves charging of the ore and fuel, removal of the slag and the matte, the collection of the flue dust and the volatilized metals, and the control of the blast.

Charging is done by means of side-dump cars through charging doors, ore, flux, and fuel being charged alternately. The slag is granulated by a stream of water which also serves to carry the slag to the dump. The matte is received in a cylindrical forehearth which holds a great quantity of metal and keeps it molten. The forehearth is tapped at intervals into a ladle which conveys the matte to the converters.

The flue dust is recovered by dust catchers in the gas downtake, just as in the case of the iron blast furnace, and is subsequently resmelted, usually after having been briquetted. The volatilized metals are recovered by straining the gases through cloth. The equipment used for this purpose, the bag-house, will be mentioned in connection with lead smelting.

The blast is usually derived from positive piston blowers or blowing engines.

In the reverberatory furnace the fuel and ore are separated, not mixed as in the blast furnace, the fuel (usually either a long-flaming bituminous coal, petroleum, or dry pulverized coal), being burned in a separate firebox, or introduced by burners at one end, and the ore is heated by the flame passing over its surface and the heat reflected from the arch of the furnace.

The reverberatory process is not a reducing process as operated for matte production. The charge must be in a condition favorable to quick melting, and therefore fine ore, not lumps, composed of silicious sulphide concentrate, roasted concentrate, and flue dust are used. Several ore charges are allowed to melt down, and then the matte is tapped as the converters require it. The slag is tapped off at a higher level from time to time, but neither slag nor matte is ever entirely tapped out. The introduction of oil fuel in certain reverberatory furnaces in this country has made possible the smelting of higher silica ores without requiring that the charge be in so finely divided a state.

The reverberatory furnace furnishes a richer matte than the blast furnace, and on this account the molten materials from the two types of furnaces are sometimes mixed before conversion in the Bessemer converter.

The conversion of the matte into metallic copper is accomplished in a Bessemer converter, the principle of operation of which does not differ essentially from that of the ordinary Bessemer steel converter. The converter is always side blown, however, and the lining is invariably a basic one made of magnesite brick.

There are two main stages in the operation of Bessemerizing copper mattes. The first is essentially the elimination of the iron sulphide; the second the final sulphur elimination. During the first stage the oxygen of the air blown into the molten matte forms oxides of iron, sulphur, and copper, and the latter immediately reacts with the remaining iron sulphide, reforming copper sulphide with the production of more iron oxide. The iron oxide now reacts with the silica which has been introduced with the charge or during the blow, and produces a great quantity of ferrous silicate slag which must be poured off at the end of this stage. The sulphur oxidizes to SO_2, which is driven off.

The product of the first stage of the operation is a " white metal," which may be considered to be practically pure copper sulphide.

The white metal is now blown to produce blister copper, the sulphur being eliminated by the action of copper oxide, first produced, on the copper sulphide present. Blowing to white metal requires about fifty to sixty minutes, and metallic copper is obtained after about sixty minutes' more blowing. The progress of the operation is judged principally by the appearance of the converter flames.

Pyrite Smelting. The term " pyrite smelting " is applied to the smelting of a pyritous ore mainly by the heat of combustion of its own sulphide constituents. The great advantage of pyrite smelting, when practicable, is that it is a process of smelting raw ore, and the expense of the usual roasting treatment is therefore saved. Pyrite smelting is practiced only by a few American smelters.

Ores suitable for pyrite smelting contain a large amount of iron sulphide, and the iron pyrites (FeS_2) loses part of its sulphur by dissociation in the upper portion of the blast furnace, leaving iron sulphide (FeS). The iron sulphide now reacts with oxygen and silica, forming a ferrous silicate slag and liberating sulphur dioxide. A considerable amount of uncombined silica or quartz is a necessary part of the charge, and the degree of concentration accomplished is controlled by varying the quartz charge.

Pyrite smelting requires more flux than ordinary smelting, on account of the slag formed. It also makes more slag, the metal loss is greater, and a stronger blast pressure is called for.

Alternate Oxidation and Reduction. This process is the old Welsh process, still used to some extent abroad but long ago abandoned in this country. It consists in a long series of alternate calcinations and fusions in the reverberatory furnace. The removal of impurities is imperfect, but the sulphur is gradually driven off and the other impurities become segregated in a portion of the product. This is the origin of the English " best selected " copper.

Refining of Blister or Coarse Copper. Electrolytic refining has come to be the method by which all the finer grades of copper are refined. Nevertheless, the older method of refining in a reverberatory furnace still possesses some commercial value and will be briefly considered.

Fire refining is based upon the scorifying effect of cuprous oxide upon base metals contained in a batch of molten copper. Air is blown upon a bath of molten coarse copper contained in the hearth of a reverberatory furnace. Cuprous oxide is very rapidly formed, and becomes dissolved in the bath. A very active oxidizing agent is thus intimately mixed with all of the molten material; the impurities become oxidized and form a slag which may be skimmed off, while the cuprous oxide is reduced to metallic copper. An excess of cuprous oxide usually remains after the removal of impurities has been carried to the practicable limit and this must subsequently be reduced by the use of a layer of charcoal or coke spread over the molten metal. Green poles are then thrust beneath the surface and in this way the dissolved cuprous oxide is gradually reduced until the oxygen content does not exceed about 0.05 to 0.07 per cent. No recovery of precious metals is possible, and the copper bars formed by casting the product are still relatively impure compared with electrolytic copper.

Electrolytic refining has displaced other methods of refining on account of the purity of the product because the precious metals are separated by the same operation.

The crude copper cast into anode plates is electrolyzed in a strongly acid copper sulphate solution. Copper is deposited on the cathode, while the impurities, including the precious metals, are insoluble in the electrolyte and fall to the bottom, forming slimes which are subsequently refined for recovery of silver, gold, etc. The purity of the cathode copper is dependent only upon the character of the electrolyte, though there is a practical limit to the degree of impurity of the anode copper.

Electrolytic cathodes commonly contain about 99.95 per cent copper, the adulterants being principally hydrogen, with perhaps 0.02 per cent of metallic impurities. The cathodes are not generally marketed without remelting in a reverberatory furnace, because their form is not one which is suitable for shipment, small pieces being easily broken off. The remelting usually partakes of the nature of a fire refinement in some measure, but this is only because of the contamination of the copper inevitably incidental to remelting. The extraordinary conductivity of cathode copper is slightly impaired by fire refinement.

Lake copper is derived from low-grade native-copper deposits which are mechanically concentrated after crushing. The resultant "mineral" contains about 85 per cent of copper. This is melted in reverberatory furnaces, the slag skimmed off, and the metal is fire refined by the method above described. In certain cases where the impurities, particularly the arsenic, run rather high, and where the content of precious metals is sufficient to pay the cost, electrolytic refining of lake copper is practiced. The resultant product is marketed as lake copper — not as electrolytic copper, however. Unless the metal is electrolytically refined, lake copper is usually sufficiently alloyed with arsenic, or phosphorus, aluminum, silica, etc., to be rendered unfit for electrical purposes because of low conductivity. The presence of these elements is not necessarily undesirable, however, because they are for the most part helpful in developing desirable mechanical properties.

Wet or *chemical methods* of derivation of copper (sometimes called *hydrometallurgical methods* or *copper leaching*) from low-grade ores or tailings usually consist in subjecting the ore to lixiviation by sulphuric acid in tanks or vats, no great difficulty being encountered in getting the copper into solution.

The precipitation of the dissolved copper is an operation which has caused more difficulty than the first stage of the process. The copper is recovered by electrolysis with considerable success.

Aside from the use of the electrolytic method, copper is most frequently recovered from solution by the use of sponge iron as a precipitant. The latter is obtained by a roasting of pyrites, followed by reduction of the iron oxide formed. The sulphur driven off in roasting the pyrite is used to make acid solvent.

5. The Properties and Uses of Copper. The properties of copper which possess the greatest practical importance are its electrical conductivity (or conversely, resistivity), and its tensile properties.

Electrical Resistivity

The maximum resistivity of various classes of copper and copper products permitted under the standard specifications of the American Society for Testing Materials is as follows, the resistivity being expressed in international ohms per meter-gram at 20° C. (68° F.):

Low-resistance lake copper wire bars (annealed)		0.15535
High-resistance lake copper (minimum)		0.15694
Electrolytic copper wire and cakes, slabs, and billets for electrical purposes		0.15535
Electrolytic copper ingots and ingot bars, cakes, slabs, and billets not intended for electrical uses		0.15694
Hard-drawn copper wire	diameters 0.460 to 0.325 in.	0.15775
	diameters 0.324 to 0.040 in.	0.15940
Medium-hard drawn copper wire	diameters 0.460 to 0.325 in.	0.15694
	diameters 0.324 to 0.040 in.	0.15857
Soft or annealed copper wire		0.15614

The electrical conductivity is principally dependent upon the purity of the copper, and the specifications for lake and electrolytic copper therefore contain the following stipulations as to the minimum metal content:

Class of Copper	*Minimum Metal Content*
Low-resistance lake copper	99.88 (silver counted as copper)
High-resistance lake copper	99.88 (silver and arsenic counted as copper)
Electrolytic copper (all shapes)	99.88 (silver counted as copper)

Tensile Properties

The tensile properties of hard-drawn, medium hard-drawn, and soft or annealed copper wire of various sizes are required to satisfy the following specifications of the American Society for Testing Materials:

Diameter. Inches.	Area. Cir. Mils.	Hard-drawn Wire.		Medium Hard-drawn Wire.			Soft Wire.	
		Minimum Tensile Strength. Lbs. per Sq. in.	Minimum Elongation. Per cent in 10 Ins.	Tensile Strength.		Minimum Elongation. Per cent. in 10 Ins.	Minimum Tensile Strength. Lbs. per Sq. In.	Minimum Elongation. Per cent in 10 Ins.
				Minimum Lbs. per Sq. in.	Maximum Lbs. per Sq. in.			
0.460	211,600	49,000	3.75	42,000	49,000	3.75	36,000	35
0 410	168,100	51,000	3.25	43,000	50,000	3.60	36,000	35
0.365	133,225	52,800	2.80	44,000	51,000	3.25	36.000	35
0.325	105,625	54,500	2.40	45,000	52,000	3.00	36,000	35
0.289	83,520	56,100	2.17	46,000	53,000	2.75	37,000	30
0.258	66,565	57,600	1.98	47,000	54,000	2.50	37,000	30
0.229	52,440	59,000	1.79	48,000	55,000	2.25	37,000	30
			Per cent in 60 Ins.			Per cent in 60 Ins.		
0.204	41,615	60,100	1.24	48,330	55,330	1.25	37,000	30
0.182	33,125	61,200	1.18	48,600	55,660	1.20	37,000	30
0.165	27,225	62,000	1.14	......	......	......	37,000	30
0.162	26,245	62,100	1.14	49,000	56,000	1.15	37,000	30
0.144	20,735	63,000	1.09	49,330	56,330	1.11	37,000	30
0.134	17,956	63,400	1.07	......	......	......	37,000	30
0.128	16,385	63,700	1.06	49,600	56,660	1.08	37,000	30
0.114	12,995	64,300	1.02	50,000	57,000	1.06	37,000	30
0.104	10,815	64,800	1.00	......	......	......	37,000	30
0.102	10,404	64,900	1.00	50,330	57,330	1.04	38,500	25
0.092	8,464	65,400	0.97	......	......	......	38,500	25
0.091	8,281	65,400	0.97	50,660	57,660	1.02	38,500	25
0.081	6,561	65,700	0.95	51,000	58,000	1.00	38,500	25
0.080	6,400	65,700	0.94	......	......	......	38,500	25
0.072	5,184	65,900	0.92	51,330	58,330	0.98	38,500	25
0.065	4,225	66,200	0.91	......	......	......	38,500	25
0.064	4,096	66,200	0.90	51,660	58,660	0.96	38,500	25
0.057	3,249	66,400	0.89	52,000	59,000	0.94	38,500	25
0.051	2,601	66,600	0.87	52,330	59,330	0.92	38,500	25
0.045	2,025	66,800	0.86	52,660	59,660	0.90	38,500	25
0.040	1,600	67,000	0.85	53,000	60,000	0.88	38,500	25
0.021	......	......	......	......	......	......	38,500	25
0.020	......	......	......	......	......	......	40,000	20
0.003	......	......	......	......	......	......	40,000	20

The gradual increase in the tensile strength requirement and the decrease in ductility called for, as the size of wire becomes smaller, is in conformity with the well-known fact that the tensile strength increases rapidly, and ductility decreases, as the amount of cold working to which the copper is subjected in drawing increases. The effect of partial and complete annealing is also recognized by the slightly lower strength values and slightly higher degree of ductility called for in the case of the medium hard-drawn wire, and the much lower strength and very much greater ductility required in the case of the soft wire.

The yield point of copper wire does not appear distinctly in tests, and the stress-strain curve exhibits no sudden break, as is the case with mild and medium steels. Tests made by members of the committee which framed the above specifications established the average value of the elastic limit of hard-drawn wires at 55 per cent of the specified ultimate tensile strength in the case of the wires more than 0.324 inch in diameter, and 60 per cent in the case of wires less than 0.325 inch in diameter. For medium hard-drawn wire the average value of the elastic limit was found to be 50 per cent of the specified tensile strength. The modulus of elasticity of drawn copper is usually found to be in the neighborhood of 16,000,000 pounds per square inch.

The tensile properties of copper in forms other than wire are not commonly specified. Hot-rolled plate shows an elastic limit usually not above 7000 or 8000 pounds per square inch, and an ultimate tensile strength of from 30,000 to 40,000 pounds per square inch. By finishing cold or by cold hammering its elastic limit may be more than doubled, while the tensile strength is increased in a lesser degree.

ZINC

6. Commercial Forms of Zinc. Zinc occurs to some extent in almost every important political division of the world, usually as a sulphide, a carbonate, or a silicate. It is used not only as metallic zinc, in which form it is known to trade as " spelter," but also in the form of zinc dust, which is formed in the distillation of zinc, and as zinc pigments, such as zinc oxide, leaded zinc oxide, and lithopone.

7. Ores of Zinc. The most important ores of zinc are zinc blende, calamine, and hemimorphite.

Zinc blende or *sphalerite* (ZnS) is the main source of zinc production. It contains 67.15 per cent of zinc when pure, but usually contains manganese, iron, cadmium, etc. *Marmatite* is a common variety containing 10 per cent or more of iron as sulphide.

Calamine or *zinc spar* ($ZnCO_3$) was formerly the chief source of zinc, but has been relegated to a secondary position, owing to the exhaustion of many deposits. Calamine is rarely pure, but contains as a rule carbonates of cadmium, iron, and manganese. When pure, it contains 52 per cent of zinc, while the presence of other carbonates may reduce the zinc content below 40 per cent.

Hemimorphite or *zinc silicate* ($Zn_2SiO_4 + H_2O$) contains 53.7 per cent of zinc when pure, and is often intermixed with, or underlies, deposits of calamine.

Franklinite (Fe, Zn, Mn)O, $(FeMn)_2O_3$, *willemite* (Zn_2SiO_4), *zincitite* or *red zinc ore* (ZnO), and *hydrozincite* or *zinc bloom* $(ZnCO_3 + 2ZnH_2O_2)$ are comparatively rare zinc ores of lesser commercial importance.

8. Extraction of Zinc from its Ores. The chemical properties of zinc are so different from those of other common metals that the metallurgical methods by which metallic zinc is derived from ores are unique, and are complex, and metallurgically imperfect. Whatever the original state of the zinc in the ore, it must be in the form of an oxide before the metallic zinc is obtainable. In this form it may be reduced by carbon at high temperatures, but this temperature is above the volatilizing point of the metal, so that it is always obtained as a vapor which must be condensed. Moreover, condensation of zinc vapor must be accomplished at a temperature above the point of fusion if the metallic zinc is to be obtained in the more commonly useful commercial form as spelter. Otherwise, i.e., by condensation at a temperature which produces solid instead of liquid metal, a powder called *zinc dust* or *zinc fume* is derived. This dust has certain special uses, but oxidizes very readily and cannot be remelted and cast to form spelter. A further complication is introduced by the fact that zinc cannot be reduced in the presence of even minute quantities of carbon dioxide without becoming oxidized, and it is therefore essential that the reduction be accomplished in the presence of an excess of carbon and in a closed retort without access of air.

Preliminary Treatment of Ores, Concentration, Calcination, and Roasting. All ores must be crushed to a finely divided state before being otherwise treated. Some measure of mechanical concentration is usually accomplished at this stage, and *flotation* concentration has been widely adopted. In this process the ore is reduced to a six-mesh size and the tailings from the jigs are finely pulverized, thickened to three parts water to one part ore, mixed with a small quantity of oil and sulphuric acid, and agitated in a tank. A float concentrate is then taken off, the gangue goes to a second-treatment tank, where the process is repeated, and finally to a third-treatment tank, where the final concentrate is taken off and the remaining gangue discharged as worthless tailings.

Calamine (zinc carbonate) and zinc silicate ores usually must be calcined prior to reduction and distillation, for the purpose of driving off the carbonic acid and water. Some anhydrous calamines and silicates are not calcined, but are reduced in the raw state. Calcination, when practiced, is accomplished in shaft furnaces, resembling lime kilns, and the operation is quite analogous to lime burning.

Blende must be roasted prior to reduction and distillation, in order to convert the sulphide into oxide as completely as possible. Any zinc remaining as a sulphide is lost in the retort residues after distillation.

The roasting operation results in obtaining zinc oxide, and is attended by the evolution of quantities of sulphur dioxide gas, which is usually collected and neutralized, because of its destructive attack upon vegetation if allowed to escape freely near the ground level. Not infrequently the SO_2 is collected and used in a by-product sulphuric acid plant.

Many forms of furnaces have been employed in roasting blende, but for the most part modern roasting furnaces are reverberatory multiple-hearth furnaces fired by coal or gas. Fig. 1 is a transverse section of such a furnace, the three lower hearths of which are muffled, i.e., the charge is out of contact with the products of combustion. Mechanical means for agitating the material and the distribution and removal of same is provided.

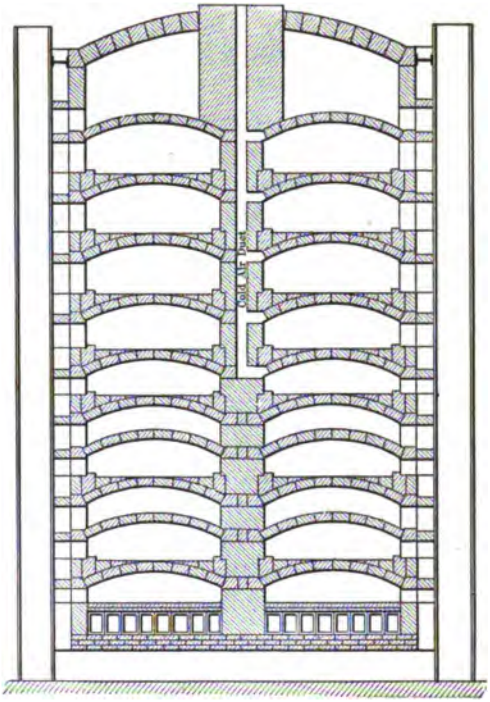

Fig. 1. — Hegeler Muffle Zinc Roasting Furnace.

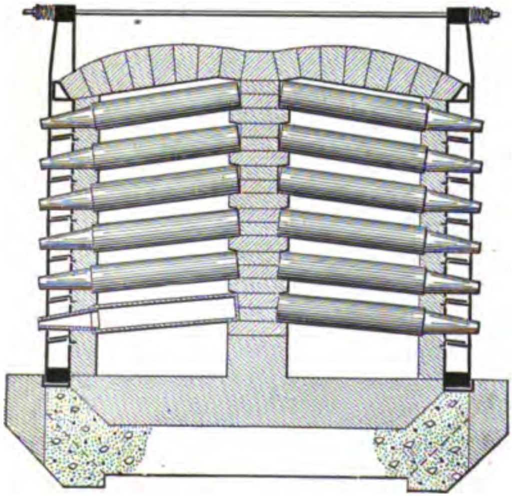

Fig. 2.—Hegeler Gas-fired Zinc Distillation Furnace.

Distillation and Condensation. The retorts in which distillation is accomplished are usually of cylindrical form, are about 8 to 10 inches in internal diameter, about 4 feet 6 inches long, closed at one end and provided with a connection with the condenser at the other end. Retorts are made with great care from specially selected clays and are molded under heavy pressure. Before firing, they are carefully dried, and when placed in the furnace must be red hot. The condensers are short clay cylinders or cones, which are attached to the end of the retort in such a manner that they may be easily and quickly detached for emptying, although luted tight to the retort while in use.

The distillation furnace consists of a long masonry chamber which is usually built with two parallel compartments, the side walls of which are simply open frames of firebrick. The retorts are placed in these chambers, the closed end being supported by projections on the longitudinal division wall, while the open end is carried by the brick framework of the face. The retort is so supported as to incline slightly downward and outward, and the condenser projects beyond the face of the brickwork, the space around it being tightly luted with clay or clay and coal. Fig. 2 shows a simple form of distillation furnace which is much used. The furnace may be heated by coal burned on grates beneath, but is commonly heated by gas, which is admitted at one end. Air for combustion is admitted at different points along the length of the furnace in order that the gas may be burned gradually. The furnace illustrated has 864 retorts, six rows high. Sometimes the number of retorts may exceed 1000 to a furnace.

The operation of the process of distillation and condensation is briefly as follows:

The retorts are charged (after the furnace is hot) with a mixture of crushed ore and coal which is packed tightly in place and then vented by thrusting in a small rod near the top of the retort. The condensers are next fitted in place and luted tight, and their mouths are partly stopped with coal to exclude air and conserve heat. The gas generated is ignited as it escapes from the mouth of the condenser until a smoky greenish flame indicates that zinc is beginning to come off. After six or eight hours enough zinc has been distilled to make it necessary to draw it by scraping the liquid zinc from the condensers to a ladle held below. The end of the condenser is now stopped with coal again and the process proceeds, the condensers being usually drawn three times, after which they are removed, the retorts scraped clean of all residue, and recharged. About twenty-four hours are required to work off a charge, which, for a furnace of the capacity illustrated, will be about 20 tons of ore.

The molten metal caught in the ladle is skimmed and immediately poured into molds. The ladle skimmings, condenser scrapings, etc., are collected and added to subsequent charges.

Refining Crude Spelter. The crude spelter, cast just as it comes from the distillation furnace, is marketed without any further treatment, so far as practice in the United States is concerned. Many spelters made in Europe are excessively high in lead, however, and must be refined. The usual practice consists in melting the bars of zinc in a reverberatory furnace.

The molten metal collects in a sump at one end of the hearth and, after the slag has been skimmed off, the pure zinc which floats on top is ladled off, the lead being drawn from time to time by means of an outlet provided in the bottom of the sump. A stratum of "hard zinc" (a difficultly fusible alloy of zinc, lead, and iron), floats upon the lead and must be removed from time to time by means of perforated ladles which allow the escape of the more liquid lead.

9. Properties and Uses of Zinc. Commercial metallic zinc or spelter contains varying amounts of impurities up to a maximum permissible amount of about 1.5 per cent for the lowest grade. The principal impurities are lead, iron, and cadmium, according to the content of which spelters are divided into the following four grades by the American Society for Testing Materials:

Grade.	Maximum Content of Lead. Per cent.	Maximum Content of Iron. Per cent.	Maximum Content of Cadmium. Per cent.	Maximum Content of Lead, Iron, and Cadmium. Per cent.
A. High grade....	0.07	0.03	0.05	0.10
B. Intermediate...	0.20	0.03	0.50	0.50
C. Brass special...	0.75	0.04	0.75	1.20
D. Prime western..	1.50	0.08		

Grades A, B, and C shall be free from aluminum.

The following tabulation is a summary of mechanical tests of cast zinc made by Gilbert Rigg and G. M. Williams. For transverse test specimens, rough castings 1¼ inches in diameter by 15 inches long were used, and were supported on a 12-inch span and centrally loaded. The tensile specimens were of the standard form used for gray iron castings, the diameter being 0.8 inch, and the length of the reduced section 1 inch. The compressive specimens were cylinders 1 inch in diameter and 2.6 inches long.

THE STRENGTH OF CAST ZINC

Grade.	Analysis per cent.			Ultimate Tensile Strength Lbs. per Sq. in.			Bending Modulus of Rupture Lbs. per Sq. in.		
	Pb	Fe	Cd	Max.	Min.	Ave.	Max.	Min.	Ave.
1. High grade..........	0.041	0.014	0.000	8,326*	4,098	6,263	12,150	11,110	11,630
2. High grade..........	0.040	0.016	0.000	4,973	4,109	4,330	11,060	10,040	10,570
1. Intermediate	0.194	0.016	0.000	5,451	3,740	4,340	10,660	9,640	10,160
2. Intermediate........	0.190	0.017	0.000	6,068	4,487	5,095	13,820	9,930	12,360
1. Brass special........	0.474	0.013	0.000	13,821*	10,125*	11,980*	22,220*	11,620	16,550*
2. Brass special........	0.484	0.031	0.000	5,351	4,098†	4,330†	16,260*	8,580†	13,110
1. Prime western No. 1.............	1.190	0.032	0.250	10,444*	4,198	7,710	12,830	8,440†	11,020
2. Prime Western No. 1.............	1.420	0.087	0.079	4,377	2,984†	3,700	10,750	9,400	10,050†
1. Prime Western No. 2.............	0.680	0.010	0.274	13,543*	7,122	10,800	18,390*	13,300	16,250*
2. Prime Western...... No. 2.............	1.150	0.011	0.046	5,331	3,640	4,670	11,350	9,390†	10,370
Dross...............	2.090	3.510	0.043	8,136	6,326	7,340	16,100	13,750	15,300

Grade.	Total Deflection in Bending on 12-inch Span Inches.			Compressive Strength 10 Per cent Compression Lbs. per Sq. in.			Compressive Strength 20 Per cent Compression Lbs. per Sq. in.		
	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.
1. High grade..........	0.280	0.220	0.250	17,710	15,170	16,600	25,080	23,500	24,239
2. High grade..........	0.300	0.200	0.250	16,700	16,130	16,400	24,000	23,430	23,640
1. Intermediate........	0.360	0.260	0.300	17,380	15,150	16,000	24,260	22,100	23,030
2. Intermediate........	0.440	0.150	0.310	17,180	15,180	16,130	23,950	22,150	23,150
1. Brass special........	0.430	0.160	0.290	20,910	19,000	20,110	28,580	27,290	28,070
2. Brass special........	0.280	0.160	0.210	18,030	16,190	17,190	25,670	23,680	23,830
1. Prime Western No. 1.............	0.160	0.090	0.130	29,450	27,210	28,270	38,870	38,640	38,770
2. Prime Western.... No. 1.............	0.200	0.100	0.130	22,780	20,020	20,950	31,390	29,280	29,970
1. Prime Western No. 2.............	0.190	0.160	0.180	29,920	27,040	28,700	39,980	38,760	39,490
2. Prime Western No. 2.............	0.220	0.170	0.190	22,080	17,710	20,080	29,990	26,730	28,450
							Max. Load, Lbs. per sq. in.		
Dross...............	0.070	0.040	0.050	35,880	35,750	35,820	38,530	30,360	34,380

*High strength value explained by finely crystalline structure.

† Low strength value explained by coarsely crystalline structure.

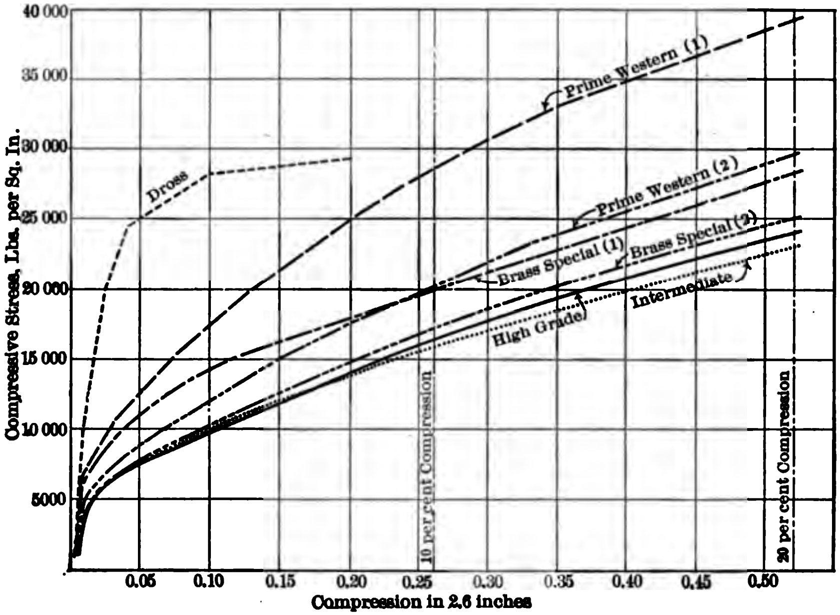

Fig. 3. — Strength of Cast Zinc in Compression. (Rigg and Williams.)

Fig. 3 gives the average stress-deformation curves for the compressive tests of the above series. The effect of the common impurities on the properties of spelters may be summarized as follows:

Lead in moderate quantities tends to make spelter softer in rolling, but weakens the coating formed in galvanizing. In quantities above about 0.7 per cent, it causes castings to crack badly.

Iron hardens spelter and renders it more brittle. An excessive amount of dross is formed in galvanizing.

Cadmium hardens spelter greatly and makes it very brittle. It is therefore particularly undesirable in galvanizing, because it is easily cracked off. Cadmium also tends to cause cracking of castings.

Spelter is largely used as a galvanizing coating; a considerable quantity is rolled into sheet zinc; a further quantity is used in making castings, one variety of which, called " slush castings," are hollow because the metal is poured back into the ladle as soon as a thin layer next the mold has solidified; and a considerable amount is used in combination with copper and other metals in making brass and other alloys.

A considerable amount of zinc is also used in the form of zinc dust. A paste of zinc dust is used in the cotton-dyeing industry under the name of " indigo auxiliary." Zinc dust is also used in the making of hydrogen in galvanizing by various dry methods, in making the electrolyte used for electro-zincing, and in the cyanide treatment of gold and silver ores.

The various zinc pigments made from zinc or zinc ore are much used. Zinc oxide is the most important of these, but leaded zinc oxide, zinc-lead oxide, and lithopone (a mixture of chemically precipitated zinc sulphide and barium sulphate) are used to a certain extent as white pigments for mineral paints.

A large amount of zinc in the form of zinc chloride is also used as a wood preservative.

LEAD

10. Commercial Forms of Lead. Lead occurs in almost every part of the world, usually as a sulphide, but sometimes as oxidized decomposition products of the original sulphide. It usually occurs associated with a small amount of silver, and often its ores contain a notable amount of antimony.

Owing to the common occurrence of the silver and antimony in lead ores, and the further fact that these metals are not removed by the ordinary process of smelting, the output of lead smelters is classed under three heads as follows:

Soft lead is derived by smelting ores which are normally so low in silver that desilverization is not necessary or practical.

Desilverized lead is that obtained by special desilverizing treatment of the ordinary argentiferous lead ores.

Antimonial lead is that which carries an average of about 17 per cent of antimony and about 2 per cent of other metals such as arsenic, copper, etc. It is, of course, an alloy and is sometimes called " type metal," since it is often used in type-founding. It is made from the ore, not from pure metals.

In addition to the forms of metallic lead above listed, lead is used commercially in the form of pigments, and as litharge. The principal forms of lead pigments are *leaded zinc oxide,* which contains from 4 to 20 per cent of lead sulphate, the remainder being zinc oxide with a small portion of zinc sulphate; *zinc lead oxide,* containing 46 to 50 per cent of lead sulphate, 52 to 46 per cent oinc oxide, and a small quantity of zinc sulphate; *sublimed white lead,* which consists of 50 to 53 per cent lead sulphate, 41 to 38 per cent lead oxide, and small proportions of lead sulphide, lead sulphite, and zinc oxide. All of these lead pigments are much used as white pigments in the manufacture of mineral paints.

Litharge is lead oxide (PbO), containing 92.83 per cent of lead. It is produced direct from ore, or may be prepared by heating metallic lead in a current of air. It is used in making flint glass, in glazing pottery, as an oxidizing agent in many processes, and has many other commercial applications.

11. Ores of Lead. The only important ore of lead is *galena* (PbS), containing 86.57 per cent of lead when pure. It usually contains silver, the amount varying from the merest trace up to about 1 per cent.

Cerussite ($PbCO_3$), containing 77.52 per cent of lead, *anglesite* ($PbSO$) containing 68.3 per cent of lead, and *pyromorphite* (Pb_3P_2O), containing 69.5 per cent of lead, are all decomposition products and occur only in the upper portions of deposits of galena.

12. Extraction of Lead from its Ore. The metallurgical processes involved in the extraction of lead from its ores comprise two main operations, namely, roasting or sintering of the ore, and smelting in the blast furnace, and a number of secondary operations, including treatment of the matte which forms a portion of the products of the blast furnace, the recovery of dust from roasting and smelting furnaces and from matte converters, and the desilverizing of the lead if the silver content is sufficient to justify it.

The methods of roasting lead sulphide ore are two forms of a process known as "blast roasting." The process consists essentially in forcing air through finely divided metallic sulphide with the object of partially removing the sulphur, oxidizing the metal, and agglomerating the material in a form suitable for use in the blast furnace.

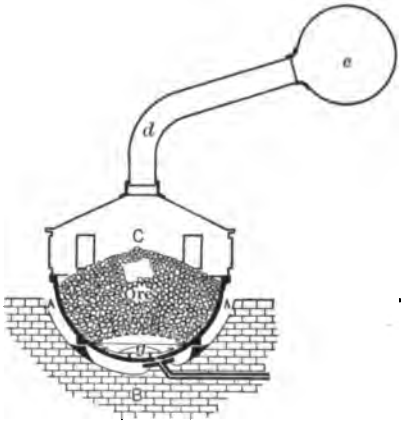

Fig. 4. — Huntington-Heberlein Lead Blast Roasting-pot.

The first of these methods, known as the Huntington-Heberlein process is an intermittent process carried out in pots which utilize the up-draft principle. Fig. 4 shows the arrangement of the blast roasting-pot. The charge, consisting of a mixture of finely divided galena concentrate and limestone, is placed in the cast-iron kettle *A* which is provided with a perforated cast-iron plate *f* which serves as a grate. A baffle plate *g* distributes the blast which is admitted through the inlet pipe below. The detachable hood *C* is now fitted in place, and the gases driven off, together with the dust which they carry in suspension, are conveyed away by the off-take **d** and the dust flue **e**. The lime-stone in the charge serves a two-fold purpose: mechanically, it accelerates the speed of roasting by keeping the particles of sulphide separate so that they may become thoroughly oxidized, and, chemically, it acts as a flux which serves to agglomerate the partly roasted ore by the formation of a silicate sinter.

The portion of the charge first placed in the kettle is usually hot roasted ore in order to facilitate the starting of the operation, and the process is continued until the sulphur content is reduced to from 4 to 8 per cent. The sinter derived as a result of the operation is broken up before being charged into the blast furnace.

The Dwight-Lloyd sintering machine, Fig. 5 utilizes the downdraft principle (with only a very shallow charge of ore to be penetrated) and is continuous in operation. The charge, in a finely divided state, is fed by a hopper into boxes or trucks called "pallets," which, in combination, form a conveyer, the continuity of which is broken at only one point in the circuit. The pallets are carried on wheels which engage guides by which they are supported. A coal-fired ignition furnace is supported above the trains of pallets, and is so arranged that the flames from the firebox are deflected down upon the ore in each pallet in succession, igniting same just before the pallet comes within the influence of the suction box. While the pallets are passing over the suction box their grate-like bottoms are in direct contact with the planed top of the suction box and all joints between the pallets are closed air tight. A downward draft through the ore to the suction box is maintained by an exhaust fan, and the ore already ignited on top is rapidly sintered. The sinter cake formed is discharged from each pallet in succession as the latter drops into the discharge guides at the end of the circuit. Sprocket wheels now again engage the pallet and gradually return it to the charging position again. The Dwight-Lloyd machine is essentially a sintering machine, and the sulphur removal is not usually carried to the ultimate extent possible in roasting.

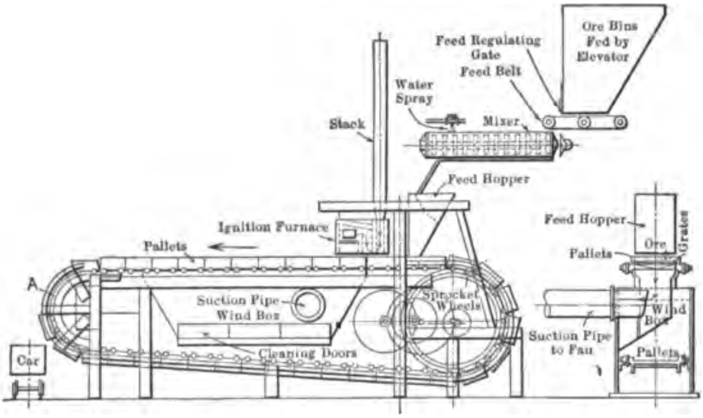

Fig. 5. — Dwight-Lloyd Straight-line Lead Ore Sintering Machine.

The smelting of lead ores is accomplished in rectangular blast furnaces which closely resemble those used in copper smelting. The furnace charge consists of sinter, matte added for remelting or enriching, a small amount of limestone and coke, and a considerable amount of slag. The blast-furnace products are metallic lead, which is tapped from the lead well directly to a molding machine; matte which contains varying amounts of lead and copper; and slag which is wasted if clean, but granulated and returned to the furnace if it contains more than 2 or 3 per cent of lead.

The operation of treating the matte for recovery of lead and copper does not differ essentially from the treatment of ordinary copper mattes in the basic converter. Separate lead and copper converters are often necessary.

The operation of the roasting or sintering furnaces, as well as the blast furnaces and converters, result in the carrying off of a great amount of metal in the shape of dust carried in suspension by the gases. The latter are therefore collected and conducted through long cooling and settling flues and finally brought to a " bag house," where the final separation of the solid material is accomplished. A great number of cotton or woolen bags, about 18 inches in diameter and 30 feet long, into which the gases are led and from which dust is collected, are vertically supported in long rows. A fan forces the gases in under light pressure, and mechanical agitation of the bags is usually provided. The material recovered in the bag house sometimes assays as high as 75 per cent lead.

Lead derived by the general methods of operation above described commonly contains varying amounts of arsenic, antimony, tin, zinc, nickel, cobalt, iron, sulphur, copper, and bismuth. in addition to silver, and their removal before marketing the lead is necessary in case they exceed limited proportions. With the exception of copper, bismuth and silver, all of these impurities are more easily oxidized than is lead, and their removal may therefore be accomplished by an oxidizing fusion. Copper, however, forms with lead an alloy which is less fusible than lead alone, and this separates out when the lead is melted as a scum which may be removed. Silver is usually removed through the agency of zinc by a special process which also removes the last traces of copper, and bismuth can only be removed with great difficulty, but is usually not present in such amounts that it need be taken care of.

Refining, for the sake of removing the impurities other than those specially mentioned above, may be accomplished to a certain degree by skimming the metal in a forehearth after it has cooled to the casting temperature, but if the impurities are present in more than a small amount the refining is commonly done in reverberatory furnaces or in melting pots. Air, sometimes assisted by the introduction of steam or lead oxide, is depended upon to oxidize the impurities. Desilverization is usually accomplished by throwing zinc onto the surface of the molten lead, melting the zinc, stirring the whole thoroughly, allowing the bath to cool and removing the scum of lead-zinc silver alloys which forms on the surface. This scum not only contains all the silver originally present, but also removes the last vestige of copper. From this mixture of alloys the zinc can be separated by distillation and the lead is subsequently separated from the silver by an oxidizing melting in a reverberatory furnace, the lead oxide formed being withdrawn in a molten condition while the silver remains behind.

13. Properties and Uses of Lead. The commercial uses of lead are of such a nature that the only physical properties commonly taken account of are its plasticity, its malleability, and its resistance to corrosion after a thin oxide film has formed on the surface. Antimony, arsenic, copper, and zinc harden lead, when present to any considerable extent, but, with the exception of antimony, they are seldom present in refined lead to an extent which renders their effect appreciable. Antimonial lead or " hard lead " is much used as type metal, bearing metal, and for shot and bullets. Lead used for rolling into sheet metal for pipes must, however, be as free as possible from antimony and arsenic as well as metallic sulphides or other hardening elements.

Lead is much used in the shape of pipe (formed by forcing molten lead through a die, against which it chills, by means of an hydraulic press), and in the form of sheet lead, used in the linings of vats, tanks, chambers, etc., for chemical manufacturing processes, and for flushings, gutters, and other roofing purposes. (Sheet lead is rolled cold after casting in the form of a comparatively thin sheet.) Tea lead is a form of very thin sheet lead, so called because used primarily in lining tea-chests. The character and uses of lead pigments and litharge have been indicated above.

TIN

14. Commercial Forms of Tin. Tin is used quite extensively in the form of sheet tin, and as tinfoil, but has almost no other commercial application except as a constituent of many valuable alloys. It is one of the few important metals which is found abundantly in other parts of the world which is not also abundant in the United States. The principal sources of tin are the Federated Malay States in the East Indies (referred to as the Straits or Straits Settlements), England, Australia, and Bolivia. In the United States, only relatively small amounts of tin are mined, the principal source being Alaska.

15. Tin ore. The only ore of tin which is used for extraction of the metal is *tin stone* or *cassiterite* (SnO_2), containing 78.6 per cent of the metal. It occurs both in lodes or veins, when it is called *lode tin*, and in secondary deposits of water-worn particles, called alluvial deposits of *stream tin.*

16. Extraction of Tin from its Ores. The extraction of tin from its ore involves the mechanical, or combined mechanical, thermal, and chemical, concentration of the ore, reduction by smelting with charcoal or coke in shaft furnaces or reverberatory furnaces, and refining of the crude tin derived by smelting.

When the ore is in the form of alluvial deposits a large proportion of the earthy material, quartz, silicates, and metallic oxide impurities may be removed by mechanical separation methods. Lode ores usually require an oxidizing roasting in reverberatory furnaces. Sulphur and arsenic are thus expelled and the metals with which they were combined are converted into oxides. These metallic oxides are subsequently removed by washing, a second roasting and washing treatment being sometimes required when the arsenic content of the ore is very high. When copper and bismuth are present, their oxides formed by roasting are removed by leaching with dilute sulphuric or hydrochloric acid before further washing.

Two-thirds of the tin produced is smelted in small shaft furnaces in which wood charcoal is used as fuel and reducing agent. Finely divided ores require the addition of a loosening agent (slags), in order to make smelting possible, and the increase in the amount of slag produced thereby increases the amount of tin lost in the slag. The furnace must be worked with a low depth of charge and low blast pressure in order to prevent excessive loss by volatilization and by the carrying off of fine dust by the blast. Dust chambers are usually provided to collect this ore dust and volatilized tin. In order that the tin may be subjected to the oxidizing blast as little as possible, the furnace is usually worked with an open tap hole, and the separation of the slag and tin is effected in a forehearth.

The reverberatory furnace is able to smelt fine ore without the addition of a slag, but coal for reduction purposes is used in addition to that burned as fuel in the separate firebox. The tin produced in the reverberatory furnace may be purer than that from the shaft furnace, and little loss is occasioned by volatilization or as flue dust. More tin is lost in the slag, however.

The slags, skimmings, furnace accretions, etc., are treated by processes of smelting with a lime flux or smelting with scrap iron, the lime or the iron serving to reduce the oxide of tin.

The crude tin obtained by the above processes must usually be refined in order to remove its impurities — iron, copper, lead, antimony, and arsenic. The most common refining treatment is simply a *liquation* process, the pure tin being melted out on a hearth and allowed to escape while the less fusible alloys of the impurities remain behind as liquation dross. Sometimes liquation is followed by *boiling* or *tossing*. The *boiling* process consists in maintaining the tin in a molten condition in a pot, the metal being agitated by the gases and vapor given off when a bundle of green twigs is thrust into the bath. This treatment brings every portion of the metal in contact with the air and the more easily oxidized metals are oxidized and form a scum on top which is skimmed off. When there is no longer any scum on the metal it is allowed to cool, in order that the heavy metals (principally copper and iron) may settle to the bottom, after which the metal is ladled into molds. The upper portion of the metal in the pot is purest, the lower layers are of intermediate quality, and the portion at the bottom is usually liquate and boiled again. *Tossing* differs from boiling only in that a workman continually takes up a ladleful of metal and pours it back into the melting pot from a considerable height, thus facilitating oxidation.

17. Properties and Uses of Tin. The properties of tin of commercial importance are its extreme malleability at ordinary temperatures, and its high resistance to corrosion when pure. A very large portion of the world's production is cold, rolled into sheet tin and used in the manufacture of cans, as roofing material, etc. A smaller proportion is used as a coating on sheet iron or steel, or as tinfoil. When heated above atmospheric temperatures it becomes brittle, until at 200° C., (392° F.), it can be powdered by hammering. Iron in considerable amounts makes tin hard and brittle and less rust resistive. Arsenic, antimony, and bismuth, in amounts exceeding about 0.05 per cent, lower its strength considerably, and copper and lead (1 to 2 per cent) increase its hardness and strength, but render it less malleable.

ALUMINUM

18. Commercial Forms of Aluminum. The first practicable processes for the production of metallic aluminum have been developed since 1886. Prior to that time the metal was merely a chemical curiosity, but in the years that have followed the discovery of electrolytic extraction methods it has assumed a position of great importance among non-ferrous metals. It is recommended particularly by its lightness (sp. gr. = 2.60–2.74) combined with a high degree of strength, great ductility, high heat and electric conductivity,. malleability, non-corrosiveness, and immunity from attack of certain acids.

Aside from its very common use as rolled, pressed, drawn, or cast metal, metallic aluminum is considerably used in the form of aluminum foil, like tinfoil, and as powdered aluminum which is used extensively as a paint pigment, in explosives, and in lithographing and in printing.

19. Occurrence in Nature. With the exception of oxygen and silicon, aluminum is the most abundant element in the world; yet there are few minerals which have been successfully used for its extraction. The most important are *bauxite* and *cryolite*, while rocks containing aluminum sulphate, kaolin, and clay are of much less importance. Whatever the original source of the material, it is converted into alumina (Al_2O_3), before the metal is extracted.

Bauxite is a mixture of alumic and ferric hydrates containing widely varying amounts of alumina, ferric oxide, silica, calcium and magnesium carbonates, water, etc. Most bauxites carry from 40 to 55 per cent alumina.

Cryolite is a double fluoride of sodium and aluminum, represented by the formula $Al_2F_6 + 6NaF$, and containing, when pure, 13.07 per cent aluminum.

20. Extraction of Aluminum. The only methods of extraction of aluminum of commercial importance consist in the electrolysis of comparatively pure alumina dissolved in a bath of molten cryolite. Alumina for the purposes of electrolysis is at present principally made from bauxite, but may be prepared by treating silicious bauxite, kaolin, or clay with sulphuric acid, and subsequently driving off the sulphuric acid from the aluminum sulphate produced, by ignition. Bauxite is treated with a soda solution, and the alumina is extracted as sodium aluminate. The alumina may be precipitated from the solution as hydroxide by carbon dioxide, and subsequently washed, filtered, and dehydrated by heating, or it may be precipitated as hydroxide by stirring the solution with pure aluminum hydroxide.

The general features of the production of aluminum by the electrolysis of alumina dissolved in molten cryolite are as follows: —

A bath is formed by the melting of cryolite in a small pot which is built of plate iron and provided with a thick carbon bottom lining. The construction of one form of electrolytic alumina reducing pot is shown in a general way by Fig. 6. Carbon anodes are suspended at frequent intervals in such a manner that they project into the bath, but do not touch the carbon cathode which forms the bottom lining of the pot. The cathode carbon is in contact with the iron shell and the latter forms the negative pole. Provision is made for raising and lowering the anode carbons.

In operation, alumina in a finely divided state is spread over the bath of molten cryolite and stirred in. Thereupon it becomes melted by the heat developed by the resistance of the bath to the passage of current, and dissolves in the bath. Electrolysis begins immediately. The aluminum migrates to the cathode, where it is precipitated, and the oxygen at the anode forms carbon monoxide gas. As the bath becomes impoverished, fresh alumina and cryolite are added from time to time. The aluminum collects on the bottom and is ladled or tapped out at frequent intervals. In large works a number of baths are arranged in series, and operation is continuous.

The details of modern methods of electrolytic reduction of alumina have not been permitted to become generally known. The temperature of the bath is 900°–1000° C., (1650°–1830° F.), the tension is 7.5 to 8.5 volts, and the current density 700 amperes per square foot of bath area.

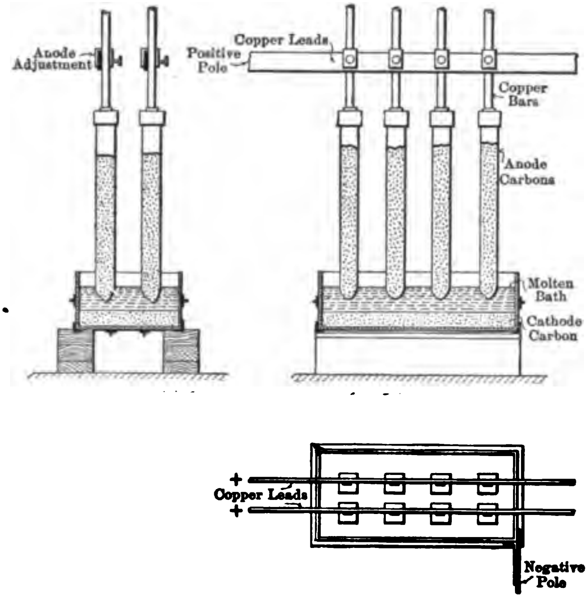

FIG. 6. — Bath for Electrolysis of Solutions of Alumina.

The early baths were completely lined with carbon, but it was later found that electrolyte which solidifies on the side walls forms all the protection required by the iron plates, the latter being cooled by circulating air

The metal derived as the product of the above operation is commercial aluminum, and is usually about 98 to 99.5 per cent pure. Special grades are obtainable, containing as much as 99.9 per cent aluminum, and some second grade metal is sold which contains not over 95 or 96 per cent aluminum. The principal impurities are silicon and iron.

21. Properties and Uses of Aluminum. The general properties of commercial aluminum are indicated by the following table. The minimum values apply to metal in an annealed condition, and the maximum values to metal that has been cold worked to an extreme degree by forging, cold rolling, or drawing, without subsequent annealing.

TENSILE PROPERTIES OF ALUMINUM*

Form	Tensile Strength Lbs. in.^{2}	Yield point Lbs. in.^{2}	Elongation in 2 inches Per cent	Reduction of Area Per cent
Sand cast	11000–13000	8500	15–25	....
Chill cast	12000–14000	9000	15–25	....
Sheet:				
Annealed	12000–15000	8000–9000	12–35	20–30
Half hard	18000–22000	9000–12000	5–1	20–30
Hard	22000–35000	12000–25000	1–7	20–30
12-gage	25000	....	7	....
16-gage	28000	....	5	....
20-gage	30000	....	3	....
Bars (hard)	28000–35000	14000–23000	....	30–40
Wire (hard)	25000–55000	16000–33000	....	40–50
40-mil	31000	....	....	....
80-mil	28000	....	....	....
120-mil	25000	....	....	....
200-mil	22000	....	....	....

The very marked effect of cold working in increasing the strength and improving the elastic properties of the metal is exhibited by the above maximum values. The ductility is very considerable, and it works well, at temperatures below about 200° C. (392° F.), in rolling or forging. Cold working hardens aluminum excessively, and in wire drawing the metal must be frequently annealed to restore ductility.

The low electrical resistance of aluminum is one of its most valuable properties, since a relatively high conductivity, combined with its lightness and strength, makes it especially well adapted for use on long-span transmission lines. Pure aluminum is being used extensively in electrical work both as bus-bars and rods in power stations and in large quantities for transmission lines with high voltages. Aluminum Wires of the same electrical conductivity as copper are enough larger so that corona losses are much less. With regard to equivalent conductivities, it has been calculated that 1 pound of aluminum is equivalent to about 2 pounds of copper so that aluminum can be used economically when the price of aluminum is anything less than twice that of copper.

Aside from the electrical uses of metallic aluminum immense quantities are used in the manufacture of many articles of every-day domestic use and in many industries where tanks, cooking vats, etc., which must be heat-conductive, non-corrosive, and non-poisonous, are used. For these purposes the metal is either cast or rolled, and many articles are finished in a press. A further quantity of aluminum is finished in the form of seamless tubing which has many important applications.

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* Circular of the Bureau of Standards. No. 76.

Aluminum may be used for casting purposes where lightness and softness are required rather than hardness and strength. Most of the aluminum used for these purposes, however, is slightly alloyed with other metals which harden it and materially increase its strength. Much of the rolled and drawn aluminum is also slightly alloyed, with an improvement in strength and hardness.

NICKEL

22. Commercial Forms of Nickel. Metallic nickel has very few commercial applications. A limited amount is incorporated with iron as ferro-nickel and used in the making of nickel steel; a further quantity is used in alloys of non-ferrous metals; and a small quantity is used as anode plates for electrolytic nickel plating of various metals. In the form of the double sulphate with ammonium ($Ni(NH_4)_2(SO_4)_2$), it is also used as the electrolyte in nickel plating.

23. Occurrence in Nature. Ores of Nickel. Nickel is a constituent of many minerals, sometimes as the principal metallic element, but more frequently as a secondary element only extracted because smelting is justified by the presence of other metals, such as copper, in the natural mixture of minerals which includes nickel compounds. The only minerals from which nickel is obtained to any considerable extent are *nickel pyrites* and the silicate *garnierite.*

Nickel pyrites or *millerite* (NiS) occurs in large quantities in the Sudbury districts of Ontario, Canada, and is found in a few other unimportant deposits. It contains 64.5 per cent of nickel and is almost invariably associated with iron and copper pyrites. The Sudbury ores average about 3 per cent of nickel.

Garnierite is a nickel-magnesium silicate of variable composition usually containing from 9 to 17 per cent of nickel oxide, with varying amounts of silicon, magnesia, ferric oxide, etc. The principal source of garnierite is on the island of New Caledonia. These ores usually contain about 7 or 8 per cent of nickel.

24. Extraction of Nickel from its Ores. The methods of extraction of nickel from sulphur compounds and from silicates will be briefly considered.

The smelting of sulphur compounds, after removal of gangue, involves principally the separation of nickel from sulphur and from iron, and in most cases from copper also. The first operation consists in roasting the pyrite ore, the methods and equipment used differing in no respect from those used in treating other classes of sulphide ores. The object of roasting is to remove sulphur until only enough remains to combine with nickel, copper, and a portion of the iron, during the smelting operation which follows. Most of the iron becomes oxidized during roasting and the sulphides of the nickel, copper, and iron are in part converted into sulphates.

The second step in the process is the smelting of the roasted ore in a blast furnace with carbon and silicious matter. All of the iron which has been previously oxidized passes into the slag, while the residue of undecomposed iron sulphide forms a matte containing all of the nickel and copper sulphides. Any oxides of nickel and copper react with iron sulphide in the blast furnace, decomposing and slagging the latter as iron silicate, and themselves becoming sulphides. The smelting furnace used resembles the copper blast furnace and the resultant coarse matte should contain 15 to 25 per cent of nickel unless the ore is very lean. In the latter case the coarse matte is enriched by a repetition of the roasting and smelting process. Complete separation of the iron cannot be effected in the smelting operation because of the loss of nickel in the slag that would result, and the next step in the operation is therefore the removal of the iron sulphide by an oxidizing fusion, the iron being converted into ferrous oxide, which combines with silica and is slagged off. This operation is accomplished in a converter, and the removal of iron is complete. Any nickel or copper which is oxidized reacts with ferrous sulphide, forming ferrous oxide (which is slagged), and sulphides of nickel or copper. It is not possible, however, to separate metallic nickel as copper is separated, by continuing the blow. The slag produced usually contains notable amounts of nickel and copper and is therefore returned to the smelter. The refined matte produced usually contains from 30 to 40 per cent of nickel, and any amount of copper up to, or slightly exceeding, the amount of nickel. Both are in the sulphide form.

The derivation of metallic nickel and copper from the refined matte is accomplished by a number of methods. The Orford process consists in removing the copper and the little residual iron by repeatedly smelting it in small blast furnaces with sodium sulphate (Glauber salt) and carbon (coal). The copper forms a complex sulphide of sodium, copper, and iron, and nickel sulphide remains behind. This is roasted to nickel oxide, which is finally reduced by carbon (charcoal) in crucibles. A considerable proportion of the nickel oxide is marketed as such, since it may be used in this form for alloying purposes.

The Mond process consists in roasting the matte, extracting part of the copper with sulphuric acid and reducing by smelting to a nickel-copper alloy. By subjecting this to the action of carbon monoxide at the proper temperature, the nickel is converted into the gaseous nickel carbonyl, and the latter is finally decomposed by heat into metallic nickel and carbon monoxide.

Electrolytic methods of refinement have also been used successfully in treating refined matte. The latter is roasted, smelted for copper-nickel alloy, and the latter electrolyzed.

The extraction of nickel from the silicate differs from the methods employed in treating sulphur compounds principally in that the initial smelting of the ore is done in a blast furnace with the addition of sulphur compounds, in order to produce a matte containing the nickel in the form of sulphide.

The ore is mixed with calcium sulphide, or with gypsum, and with coal or coke. The mixture is crushed to powder, pressed into briquettes, and charged into the blast furnace. If gypsum is used it is reduced to calcium sulphide by the carbon in the furnace, and the calcium sulphide is decomposed by the nickel silicate of the garnierite, nickel sulphide and calcium silicate being formed. The resultant matte is rather richer in nickel sulphide than that obtained in smelting sulphur compounds, and the subsequent separation of the iron sulphide, the refinement of the second matte, and the final derivation of metallic nickel is accomplished by practically the same methods that are used in treating matte from sulphur compounds.

25. The Properties and Uses of Nickel. The most important property of nickel, aside from the advantages which it may confer upon steel or non-ferrous metals with which it is alloyed, is its non-corrosiveness. On this account and because of its silvery appearance, one of the commonest commercial applications of metallic nickel is in plating iron, steel or other metals. Its mechanical properties are excellent, sometimes equaling those of medium-carbon steel, but it is too expensive for general use. It is quite ductile, and fairly malleable, but is rendered brittle and incapable of being rolled by not more than 0.1 per cent of arsenic or sulphur. Most of the other impurities common to commercial nickel are not injurious to its properties, and some are beneficial in limited amounts.

The Non-Ferrous Alloys

26. The Non-ferrous Alloys in General. The study of metallic alloys is a very complex one, not only on account of the great number of combinations of two or more metals which have been found to possess valuable attributes, but also because of the inherent complexity of the problem of the interaction of metals combined in a state of fusion. True alloys of metals are never mechanical mixtures of the constituents, but are either (*a*) solid solutions of the metals (*b*) solid solutions of a chemical compound of the metals in the metal which is in excess, or (*c*) mixtures of such solutions with definite substances which have crystallized out during cooling. The composition, constitution, and structure of many alloys may therefore vary widely, and the physical characteristics likewise vary, and can be predicated upon a knowledge of the properties of the constituent metals to only a slight extent.

Many important investigations of the more important alloys, or groups of alloys, have been made in recent years, and no small portion of our present knowledge of the subject has been gained through the application of modern methods of research in physical chemistry, by the use of microscopic methods, and by study of the phenomena of fusion and solidification.

These studies have an important bearing upon the study of purely physical properties which alone possesses a direct interest for the engineer or artisan. In the present discussion of the subject, however, no effort will be made to cover anything more than the composition, physical properties, and uses of the alloys which possess a distinct commercial importance.

COPPER-TIN ALLOYS. BRONZES

27. Ordinary Bronzes. Alloys of copper and tin are among the most useful of all the non-ferrous alloys, and have been known and used since prehistoric times. The influence of tin upon the properties of copper is that of a pronounced hardener and strengthener, so long as a limiting percentage of 20 or 25 per cent is not exceeded. The range of composition of ordinary commercial bronzes is not wide, all of the important ones containing 80 per cent of copper or more.

Fig. 7 presents a summary of the mechanical properties of a series of bronzes tested by the U. S. test board under the supervision of Professor Robert H. Thurston.* In spite of the exercise of the greatest care in conducting the investigation, the properties of the individual specimens of the 29 alloys tested varied widely, and the comparatively smooth curves of Fig. 7 simply average up the results in a general way. All of the specimens used in this series of tests were of cast bronze, the transverse test specimens being the original cast bars 1 inch square in section and centrally loaded on a span of 22 inches. The tensile specimens were turned from the ends of the transverse test specimens, the reduced portion being 6 inches long and 0.798 inch in diameter (0.5 sq. in. in area), and deformations were measured on a 5-inch gauged length. The compressive specimens were cylinders 2 inches long and 0.625 inch in diameter turned from the ends of the tensile specimens.

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* Report of U. S. Board to Test Iron, Steel, and Other Metals, 1881.

The bronzes exhibiting the greatest tensile strength and bending strength, and the highest yield point, are those containing more than 80

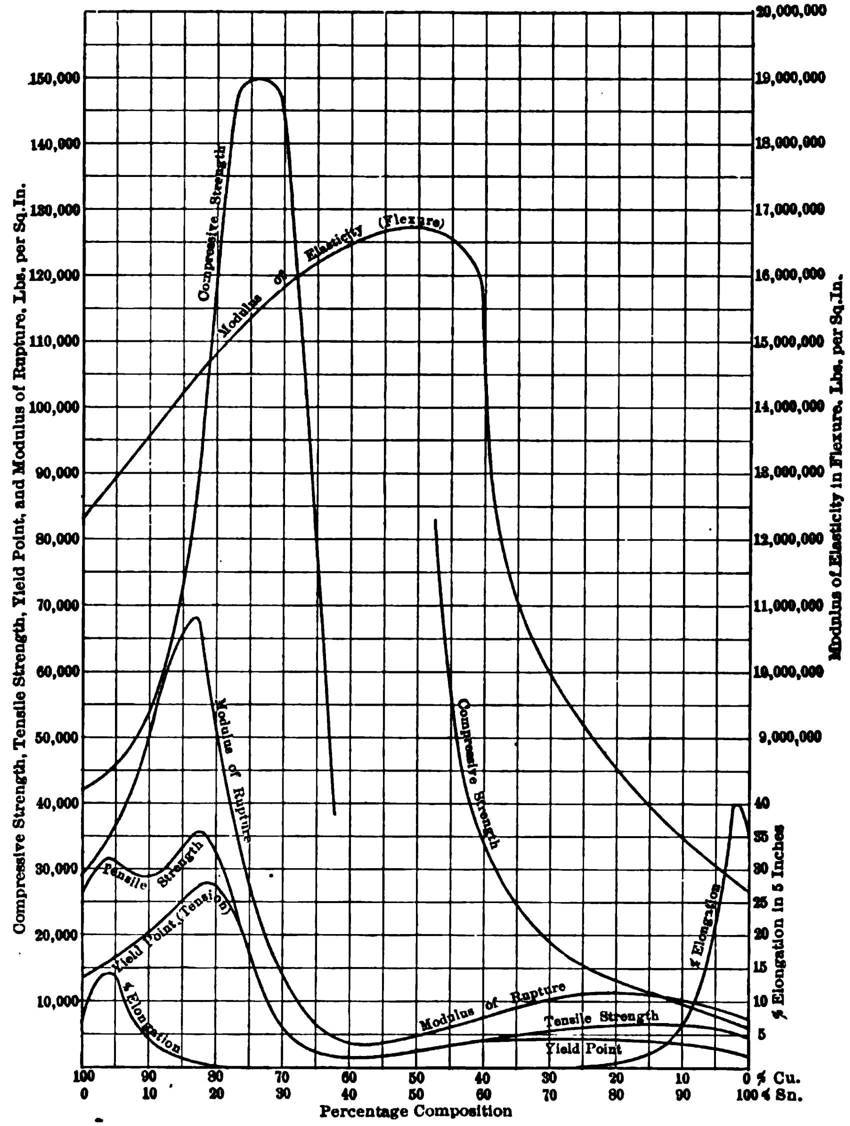

FIG. 7. — Properties of the Copper-Tin Alloys. (U. S. Test. Board.)

per cent of copper. The compressive strength appears to increase with decrease in copper content until an alloy containing about 75 per cent of copper and 25 per cent of tin is passed. Beyond these limits the strength decreases rapidly in all cases with further additions of tin. The stiffness appears to increase until a 50 per cent tin alloy is reached, but the ductility reaches its maximum with only about 4 per cent of tin, and is entirely lacking with more than 25 per cent of the latter, until alloys are reached which begin to approach pure tin in properties, when the great ductility of the latter comes to be characteristic of the high-tin alloys. All of the alloys containing between 25 and 75 per cent of tin are extremely brittle and weak, and those containing more than 75 per cent of tin are weak and soft.

The strength and ductility of bronzes are considerably affected by heat treatment. M. Guillet* found that, with bronzes containing over 92 per cent of copper, quenching between 400° C. (752° F.) and 600° C. (1112° F.) slightly increases the strength and ductility. With less than 92 per cent of copper, both strength and ductility increase decidedly as soon as the quenching temperature exceeds 500° C. (932° F.). The maximum strength of all alloys was found to be reached by quenching at about 600° C. (1112° F.), the beneficial effect becoming more marked as the copper content is reduced.

The most commonly used types of ordinary bronzes are the following (it will be noted that a number of these alloys classed as ordinary bronzes sometimes contain small amounts of zinc, lead, etc.).

Machinery bronzes are used principally as hard bearing metal, as metal for cut gears, and for valves, bushings, stuffing boxes, piston rings, steam whistles, plumbing fixtures, etc. The average machinery bronze contains from 81 to 87 per cent of copper, and 19 to 13 per cent of tin. Most gear bronzes contain phosphorus or manganese or both, and will therefore be considered under the head of "special bronzes." Frequently bearing bronzes contain from 2 to 4 per cent of zinc, as do also many of the bronzes used for the various machine parts above listed. Locomotive bronzes and piston rings may contain as much as 8 or 9 per cent of zinc. (The properties of the ternary bronzes are considered in the following article.)

Gun metal usually contains from 88 to 92 per cent of copper and 12 to 8 per cent of tin. It is one of the strongest of all the bronzes. It was at one time commonly used for casting guns and is now used as a material for strong castings. It is not infrequently alloyed with small percentages of zinc or even lead.

Bell metal usually contains from 75 to 80 per cent of copper and 25 to 20 per cent of tin. It is largely used for bell founding, because of its resonance, but is hard and brittle. (A number of brasses and ternary

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* "Etude Industrielle des Alliages Metalliques," 1906.

alloys are also used in bell founding.) Small amounts of zinc or lead are occasionally used in bell metal, and silver is sometimes added with the idea that the tone is improved.

Speculum metal usually contains 65 to 70 per cent of copper and 35 to 30 per cent of tin. Before the present state of the art of manufacturing silvered glass reflectors was attained it was always used for the specula of reflecting telescopes. Its value is due to the fact that it is extremely hard, and therefore takes a smooth polish, and possesses a silvery white color.

Statuary bronzes usually contain from 90 to 78 per cent of copper, 2 to 10 per cent of tin, and any amount of zinc up to 10 or 15 per cent. They often contain more zinc than tin, and therefore ought to be classed as special bronzes or brasses.

Coin or *medal bronzes* contain from 90 to 97 per cent of copper and 10 to 3 per cent of tin. Occasionally very small amounts of zinc or lead are added.

28. Special Bronzes. *Copper-tin-zinc* Bronzes. The copper-tin-zinc alloys are among the most valuable and commonly used of all the bronzes. The range of composition of the commercial bronzes of this class is from 50 to 95 per cent of copper, 1 to 15 per cent of tin, and 5 to 50 per cent of zinc.

The tensile strength of copper-tin-zinc alloys is exhibited by the diagram of Fig. 8, which is based upon the report of the U. S. Board above referred to. The triaxial diagram used in this instance is based upon the geometrical principle that the sum of the normals from any point in an equilateral triangle upon the sides is equal to the altitude of the triangle. The altitude is made to represent 100 per cent of any of the constituents. Thus the altitude measured to one vertex from the opposite side represents 100 per cent of copper, that to the second vertex 100 per cent of tin, and that to the third vertex 100 per cent of zinc. Each side of the triangle represents zero content of the constituent represented by the opposite vertex, and the distance of a point within the triangle to any side, expressed as a proportion of the altitude, expresses the percentage of the constituent represented by the vertex opposite the side chosen. Any point in the diagram therefore represents a certain definite alloy or mixture of three constituents. Thus point **A** on the diagram represents an alloy containing 13 per cent of copper, 57 per cent of tin, and 30 per cent of zinc. Each alloy tested is therefore represented by some one point on the diagram, and when all such points have been plotted and marked with the figures representing the particular property under investigation (tensile strength in this case), lines or contours may be drawn connecting points representing alloys possessing the property in question to an equal degree, and the result is such a diagram as is here presented.

It is evident at a glance that all of the alloys possessing sufficient strength to be considered of any value are those containing more than 50 per cent of copper, less than 20 per cent of tin, and less than 50 per cent of zinc. The strongest alloys contain nearly 60 per cent of copper, 1 to 2 per cent of tin, and nearly 40 per cent of zinc. The diagram does not show the ductility of the various alloys, but the data of the original tests reveal the fact that the most ductile alloys are in the upper portion of the field comprised within the 30,000-pounds-per-square-inch contour line. All of the alloys containing more than 10 to 20 per cent of tin (the higher, the lower the zinc content), are extremely brittle and fragile, and are altogether worthless. The alloys having a tensile strength of from 30,000 to 40,000 pounds per square inch are the most generally useful ones, since they are comparatively tough and are very ductile, showing from 10 to 30 per cent elongation at rupture in tension.

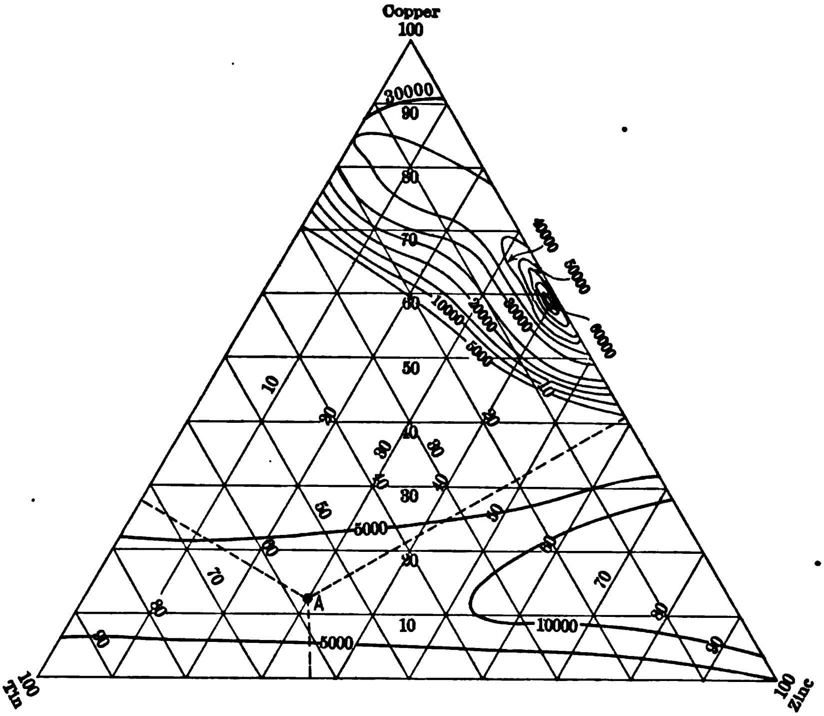

FIG. 8. — Tensile Strength of Copper-Tin-Zinc Alloys. (Compiled by J. B. Johnson from Report of U. S. Test Board.)

The character and uses of the most important copper-tin-zinc bronzes have been indicated above under the head of machinery bronzes.

Copper-tin-lead Bronzes Lead is not infrequently added to bronzes used for bearings, for the purpose of increasing the plasticity just enough to allow the metal to adapt itself to the running surface so that the bearing is uniform over the whole surface. The addition of from 10 to 40 per cent of lead to a bronze containing 5 to 10 per cent of tin cuts down the wear on the bearing very materially without increasing the friction more than very slightly. The degree of softness desirable in a bearing bronze is dependent upon the conditions of service, and the lead content and tin content are varied accordingly. In general, the lower the content of tin, the higher the content of lead desirable. Several alloys of this class commonly used for railway service and other purposes are known as "plastic bronzes." They contain 50 to 70 per cent of copper, 30 to 50 per cent of lead, and 0 to 5 per cent of tin. Small percentages of other elements, nickel for example, are usually added to prevent segregation of the lead.

Phosphor Bronze. The addition of very small percentages of phosphorus to any bronze has a remarkable effect upon its properties. The tensile strength is considerably increased, and the elastic limit and endurance under repetition of stress are very greatly increased. Phosphorus added in small amounts acts principally as a deoxidizer, and the marked improvement in the properties of the bronze is principally due to the elimination of copper oxide. In slightly larger quantities the phosphorus combines with copper to form a compound which greatly hardens the bronze.

Phosphor bronzes intended for use as engine parts, valve metal, etc., usually show only traces of phosphorus and contain about 7 per cent of tin. Phosphor bronze for gears is harder, owing to the presence of 8 to 12 per cent of tin, and phosphorus varying from mere traces up to a maximum of about 0.2 per cent. Bearing bronzes most commonly contain 8 to 10 per cent of tin and from 0.2 to about 0.9 per cent of phosphorus. Certain bearing bronzes, particularly those for railway service contain about 10 per cent of lead in addition to 10 per cent of tin and about 0.3 per cent of phosphorus. These bronzes excel any other class of bearing metal in resistance to wear under severe conditions, and in addition possess a very low coefficient of friction.

Phosphor bronzes of proper composition may be rolled or drawn into wire, and when so fabricated exhibit about the same tensile properties as does medium structural steel. Working cold has the same effect that it has in the case of steel, the strength, and especially the elastic limit, being raised to a marked extent. All of the phosphor bronzes are remarkably resistant to corrosion and are much used on subaqueous construction and in other situations on this account.

Manganese Bronze The so-called manganese bronze, which is now commonly used for a great variety of purposes, is really a special brass, since it contains very large amounts of zinc and little or no tin. This class of alloys will therefore be considered under the head of special brasses.

Silicon Bronze. Silicon added to ordinary bronzes has about the same effect as similar additions of phosphorus. Its principal action added in small quantities, is that of a deoxidizer, and it has about the same effect upon the properties as has phosphorus, the strength and especially the elastic limit being raised, although only a trace of silicon may appear in the finished bronze.

In one important respect silicon differs in its effect from phosphorus. The latter, even in very small amounts, is very detrimental to electrical conductivity, but silicon is not. In consequence, silicon bronze is a much better conductor than phosphor bronze, and is considerably used for telephone wires, etc.

Aside from its electrical conductivity, silicon bronze possesses most of the valuable properties of phosphor bronze, and is used for similar purposes where a strong, hard, and non-corrosive alloy is desired in the form of castings, rolled sections or sheets, or drawn wire.

Aluminum Bronze. The alloy commonly known as aluminum bronze contains no tin, but is simply an alloy of copper and aluminum, and so is not really a bronze at all. Its character and properties will be considered under the head of binary alloys of copper other than bronzes and brasses.

Vanadium Bronze. Vanadium has occasionally been added to bronzes in very small amounts with remarkably beneficial effects upon properties. These bronzes have not become commonly known or used, however.

Nickel bronzes are for the most part quaternary alloys containing about 30 to 40 per cent of lead, 5 per cent of tin, and 1 per cent of nickel, the balance being copper. The nickel serves particularly to prevent the separation out of lead during solidification, and produces a homogeneous alloy containing more lead than can ordinarily be used without danger of segregation. This alloy is an important bearing bronze and is considerably used in machine construction and for railway service.

COPPER-ZINC ALLOYS. BRASSES

29. Ordinary Brasses. Alloys of copper and zinc, with or without addition of other elements (i.e., ordinary brasses or special brasses), share with the bronzes the most important position among non-ferrous alloys. The influence of zinc upon the properties of copper is in the direction of increasing both strength and ductility, so long as certain limiting percentages are not exceeded, but these limiting percentages are much higher than in the case of tin, zinc being a less potent element than tin in similar amounts.

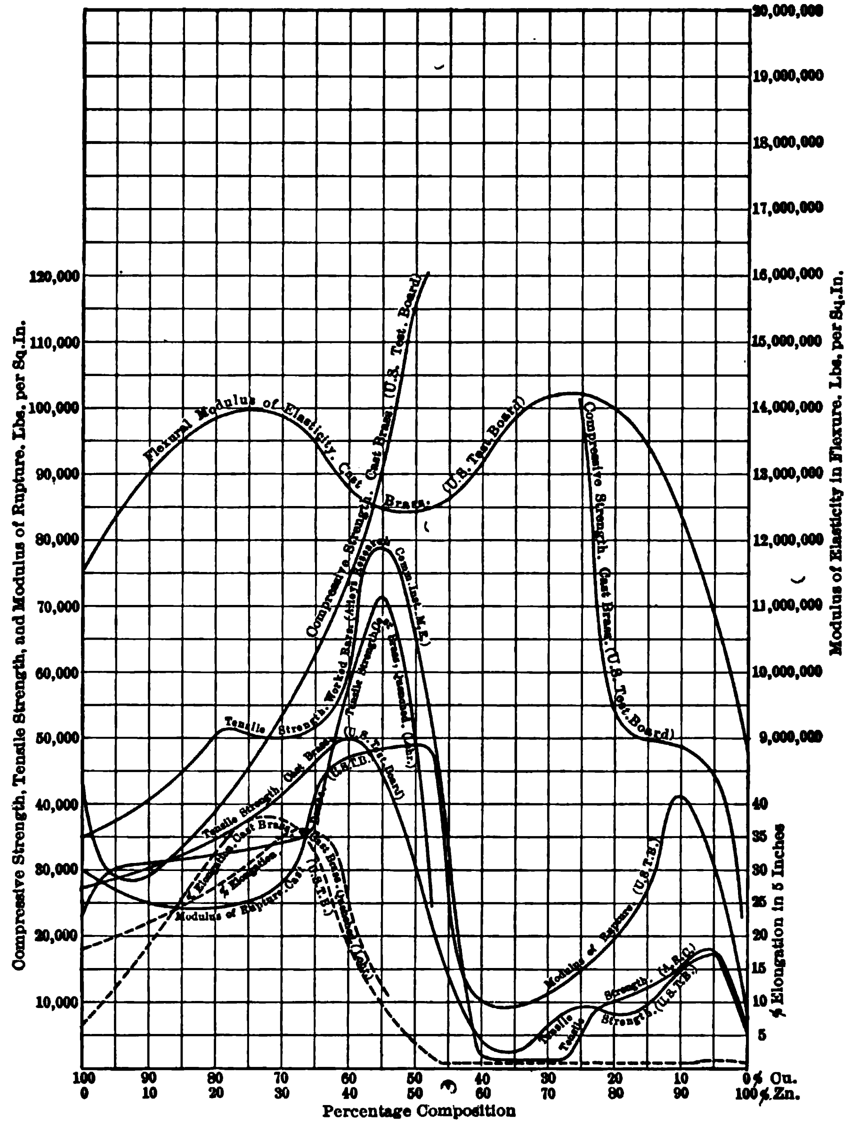

FIG. 9. — Properties of the Copper-Zinc Alloys.

Fig. 9 presents a summary of the mechanical properties of the copper-zinc alloys. The curves are based upon the report of the Committee on Alloys of the United States Board,* the fourth report of Professor W. C. Roberts-Austen to the Alloys Research Committee of the Institution of Mechanical Engineers,† and an independent study of the tensile strength of the copper-zinc alloys by Dr. J. M. Lohr.‡

The addition of zinc to copper gradually increases the strength in tension until about 30 or 35 per cent is present. Further additions rapidly increase the strength until a maximum beneficial effect is obtained with about 45 per cent of zinc. A rapid falling off in strength occurs with additions of zinc beyond 45 per cent, and the brasses containing more than about 50 per cent of zinc are brittle and worthless. (In the series of brasses tested by Thurston the gain in strength is fairly uniform with increase in zinc content up to a maximum at about 40 per cent of zinc, the strength thereafter falling off rapidly.)

The beneficial effect of preventing coarse crystallization by quenching the castings is shown by a comparison of the results of Lohr with those of Thurston, the strongest alloy of the former showing a tensile strength of about 72,000 pounds per square inch, with 45 per cent of zinc, as compared with one having a tensile strength of about 50,000 pounds per square inch with 40 per cent of zinc. The beneficial effect of mechanical working is also shown by a comparison of the curve representing the results of Roberts-Austen with that representing the results of Lohr.

The strongest cast brasses in compression appear to be those containing between 50 and 70 per cent of zinc; the maximum strength in flexure corresponds to the maximum tensile strength; and the maximum ductility is shown by alloys containing from about 25 to about 35 per cent of zinc. The strongest brasses show very low ductility.

A comparison of the curves of Fig. 9 with those of Fig. 7 shows that the best of the brasses excel the best of the bronzes in tensile strength and ductility, but the latter seem to excel in compressive strength.

The various common commercial forms of brasses may be classified as follows according to composition and uses.

Tombac and *pinchbeck* contain 85 to 90 per cent of copper and 15 to 10 per cent of zinc. They take a good polish and are principally used for ornaments, imitation of gold, etc.

Hard brazing metal contains 80 to 90 per cent of copper and 20 to 10 per cent of zinc. That containing 20 per cent of zinc is known as " quarter metal " and is considerably used for the purpose indicated by the name.

Red brass usually contains about 80 per cent of copper and 20 per cent

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* Report of U. S. Board to Test Iron, Steel, and Other Metals, 1881

† Proceedings of the Institution of Mechanical Engineers, 1897.

‡ Journal of Physical Chemistry, Vol. 17, No. 1, Jan., 1913.

of zinc. The name is used loosely, however, to cover any of the high-copper brasses which possess a reddish color, especially after pickling in acid. This class of brass is much used for ornamental work and soft castings.

Standard brass (α brass) contains about 66 to 70 per cent of copper and 34 to 30 per cent of zinc. It is the most generally useful and most commonly used of all brasses. It is very ductile, works well hot or cold, and can readily be rolled into sheets and drawn into tubes or wire. It is less easily corroded than any of the brasses of lower copper content, and is especially adapted for use in locomotive and steamship boiler and condenser tubes. Practically all ordinary sheet brass and drawn brass is of this composition, and the best of the brass castings contain about 66 or 67 per cent of copper.

Muntz metal is a brass containing 60 per cent of copper and 40 per cent of zinc. It can only be rolled hot, but was formerly much used as a sheathing for wooden vessels. Sea water attacks it and forms zinc salts, which prevent the fouling of the bottoms of ships by living organisms such as barnacles, etc.

Yellow brass contains from 48 to 56 per cent of copper and 52 to 44 per cent of zinc. A mixture of approximately equal proportions of the two constituents is commonly used in making brass castings which do not require great strength or toughness. At a red heat yellow brass becomes so brittle that it may be easily pulverized, and in this form is much used for yellow solder for brazing purposes.

White brass solder contains 34 to 44 per cent of copper and 66 to 56 per cent of zinc. It is extremely weak and brittle and is used only in a powdered condition for brazing purposes.

White brass contains less than 10 per cent of copper and more than 90 per cent of zinc. The metal possesses most of the characteristics of zinc, but is somewhat hardened and strengthened by the small amount of copper used, the coarse crystalline structure of cast zinc being largely destroyed. The material is principally used in making ornaments which are plated with bronze and sold under the name "French bronze."

30. Special Brasses. *Copper-zinc-lead brasses.* The addition of small percentages of lead softens brass and renders it more easily cut by machine tools. The presence of the lead lowers the strength and decreases the ductility considerably. More than 5 per cent of lead cannot be profitably used because of the danger of segregation, and the usual addition is not in excess of 3 per cent.

Copper-zinc-aluminum brasses. Aluminum is added to brass in amounts up to about 5 per cent with beneficial effects upon the tensile properties. The tensile strength and elastic limit are considerably raised, and the hardness increased and ductility decreased. The effect of aluminum upon the tensile strength and ductility of rolled and cast brass is exhibited by Fig. 10 which is based upon tests reported by M. Guillet.* The addition of aluminum is also beneficial in that it facilitates the making of good brass castings. Aluminum brass is principally used in making castings for machinery, marine work, etc., for forgings, and for rolled bars, plates and shapes designed for any purpose requiring a strong brass, or a strong and non-corrosive metal.

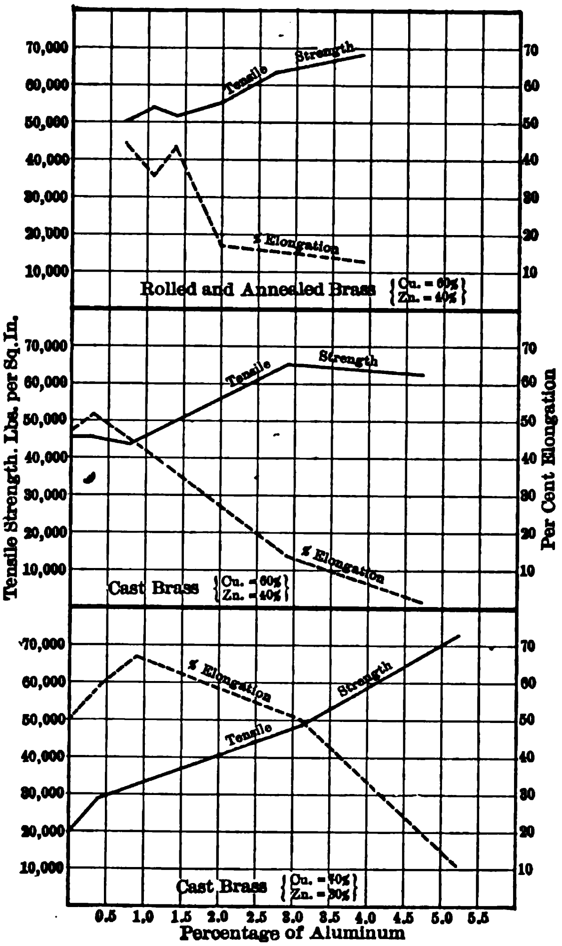

Fig. 10. — Effect of Aluminum on Tensile Properties of Brass. (Guillet.)

Copper-zinc-manganese alloys. Manganese bronze. The most valuable copper-zinc alloy in use at the present time is the so-called "Manganese Bronze." The presence of small amounts of manganese in the finished alloy is beneficial to strength in a measure, but the commercial alloy known by this name is simply a brass with which a small amount of manganese, in the form of ferro-manganese, or manganese-copper produced in the electric furnace, has been incorporated while molten for the sake of the important deoxidizing effect which the manganese exerts. The resultant alloy usually contains no manganese, or only a trace, because it has been oxidized out and fluxed off.

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* "Etude Industrielle des Alliages Metalliques," 1906.

The specifications of the American Society for Testing Materials* for manganese bronze ingot metal for sand castings call for an alloy having the following composition and tensile properties:

Chemical Composition. Per cent.	Minimum Tensile Strength. Lbs. per Sq. in.	Minimum Elongation. 2 Inches. Per cent
Copper, 53-62 Zinc, 36-45 Aluminum, 0.05-0.5 Lead, not over 0.15	70,000	20

The average composition of the commercial alloy, according to Mr. C. R. Spare,† is about 56 to 57 per cent of copper, 38 to 40 per cent of zinc, about 1 per cent of tin and 1½ per cent of iron. The iron is present inadvertently, owing to the use of ferro-manganese as the deoxidizer, and a little aluminum is introduced to facilitate the making of cast maganese bronze, but is considered undesirable in bronze intended for forging or rolling.

The range of composition of various brands of manganese bronze is quite wide and the properties of the metal vary accordingly. A soft grade is made especially for use in situations where it must withstand shock and vibration, as in naval ordnance construction. This metal has a tensile strength of about 60,000 pounds per square inch with an elongation of 40 to 50 per cent in 2 inches. A very hard grade is made which has a tensile strength of 90,000 to 100,000 pounds per square inch with elongation of 15 to 25 per cent.

The average grade of manganese bronze shows about the following properties:

	Tension.			Compression.	
	Elastic Limit. Lbs. per Sq. in.	Tensile Strength. Lbs. per Sq. in.	Elongation 2 Ins. Per cent.	Elastic Limit. Lbs. per Sq. in.	Compressive Strength. Lbs. per Sq. in.
Cast manganese Bronze	30,000 to 40,000	70,000 to 80,000	20 to 35	35,000 to 40,000	90,000 to 100,000
Rolled or forged manganese bronze	40,000 to 50,000	80,000 to 110,000	15 to 30	50,000 to 60,000	130,000 to 150,000

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* Yearbook, 1914.

† Proc. Am. Soc. Test. Matrls., Vol. 8, p. 395.

Probably no other metal or alloy possessing equal strength and toughness can be cast in intricate forms so successfully as can manganese bronze. In addition, it is particularly resistant to corrosion by sea water and alkali waters, and is proof against attack by dilute acids. Manganese bronze is very commonly used for steamship propellers, and is much used for other ship fittings, for piston rods, shafts and axles, and for all manner of castings, forgings, etc., used in general machine construction, and in locomotive and automobile construction. It has many applications in subaqueous work of various types, and has also been found to be one of the best materials obtainable for the blades of high-speed steam turbines. For the latter application it not only possesses the high strength required, but also resists the corrosive action of high pressure steam very well.

Copper-zinc-iron alloys: Two brass alloys containing iron have been commonly used. *Sterro metal* contains about 60 per cent of copper, 38 to 38.5 per cent of zinc, and 1.5 to 2 per cent of iron. *Delta metal* varies in composition, but usually contains about 55 per cent of copper, 41 per cent of zinc, 3 per cent of iron, and 1 per cent of manganese, phosphorus, and other elements. These metals, particularly the delta metal, possess a considerably higher strength and better working qualities than the brass would possess without the iron addition. They are also more resistant to corrosion. They possess, to a lesser extent, the characteristic properties of manganese bronze and aluminum brass, and have been adopted for the same class of uses, principally on marine construction.

Other special brasses. *Vanadium* is a metal which is only very rarely used in brasses. *Phosphorus* is also occasionally used in small amounts for the purpose of deoxidizing the copper, but neither vanadium brass nor phosphorus brass are alloys possessing any commercial importance. A number of quite important alloys of copper, zinc, and nickel are made and sold — usually under the name of " German silver." These latter alloys will be considered under the head of *Nickel Alloys.*

BINARY ALLOYS OF COPPER OTHER THAN BRONZES AND BRASSES

31. Copper-Aluminum Alloys. The alloys of copper and aluminum are the most valuable of the copper alloys other than the bronzes and brasses. The principal commercial alloy of copper and aluminum is the so-called *aluminum bronze,* which usually contains from 90 to 95 per cent of copper and 5 to 10 per cent of aluminum. Since no tin is present, the alloy is not really a bronze, but it is, nevertheless, commonly called " aluminum bronze," perhaps on account of its resemblance to some of the bronzes in its properties.

The characteristics of the copper-aluminum alloys have been made the subject of an extremely painstaking investigation by the Alloys Research Committee of the Institution of Mechanical Engineers.* Fig. 11 constitutes a summary of the results obtained in a portion of the investigation of tensile properties of a series of copper-aluminum alloys containing up to 13 per cent of aluminum.

The addition of aluminum to copper is shown to be responsible for a gradual raising of the tensile strength and yield-point, and a rapid increase in ductility, until about 7.35 per cent of aluminum is present. Further additions cause a more rapid raising of the strength and yield-point, accompanied by a very rapid decrease in ductility, until an alloy of maximum strength (60,000 to 74,000 pounds per square inch for castings) is reached with about 10 per cent of aluminum present. With additions of aluminum beyond 10 per cent, the strength rapidly falls off and the ductility becomes practically *nil,* the yield-point coinciding with the ultimate strength with about 13 per cent of aluminum present.

Comparing the properties of the casting made in sand with those cast in chills, it appears that chilling scarcely affects the properties of alloys containing less than 6 per cent of aluminum, but raises the strength and yield-point of the higher-aluminum alloys in proportion to the aluminum content. The strength of the chilled 10 per cent aluminum alloy is about 20 per cent higher than that of the corresponding sand-cast alloy.

The 1¼ inch rolled bars were produced by hot rolling of an ingot cast 3 inches in diameter, but turned down to about $2\frac{13}{16}$ inches, so that the reduction in rolling was from this diameter down to 1¼ inches. The rolled bars show practically the same ductility as the cast bars, but excel the latter slightly in tensile strength and yield-point. The beneficial effect of rolling was found to be only slightly increased when the reduction in rolling was continued down to $\frac{13}{16}$ inch diameter.

The cold-drawn bars were produced by rolling hot from 1¼ inches down to $\frac{15}{16}$ inch, cold drawing to $\frac{7}{8}$ inch, annealing, and then cold-drawing down to $\frac{13}{16}$ inch. The effect of cold-drawing to this moderate extent appears to be a moderate increase in tensile strength, a great raising of the yield-point, and a great loss of ductility.

The effect of slow cooling from 800° C. (1472° F.), and the effect of quenching from the same temperature were also investigated and led to the conclusion that slow cooling from this temperature has no effect upon alloys containing less than 7.35 per cent of aluminum, and injured the higher-aluminum alloys, owing to coarse crystallization and consequent brittleness. Quenching was found to have no effect upon the alloys

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* Proceedings Institution of Mechanical Engineers, 1907, p. 57.

below 7.35 per cent aluminum, but greatly raised the tensile strength and yield-point, and lowered the ductility of the higher-aluminum alloys.

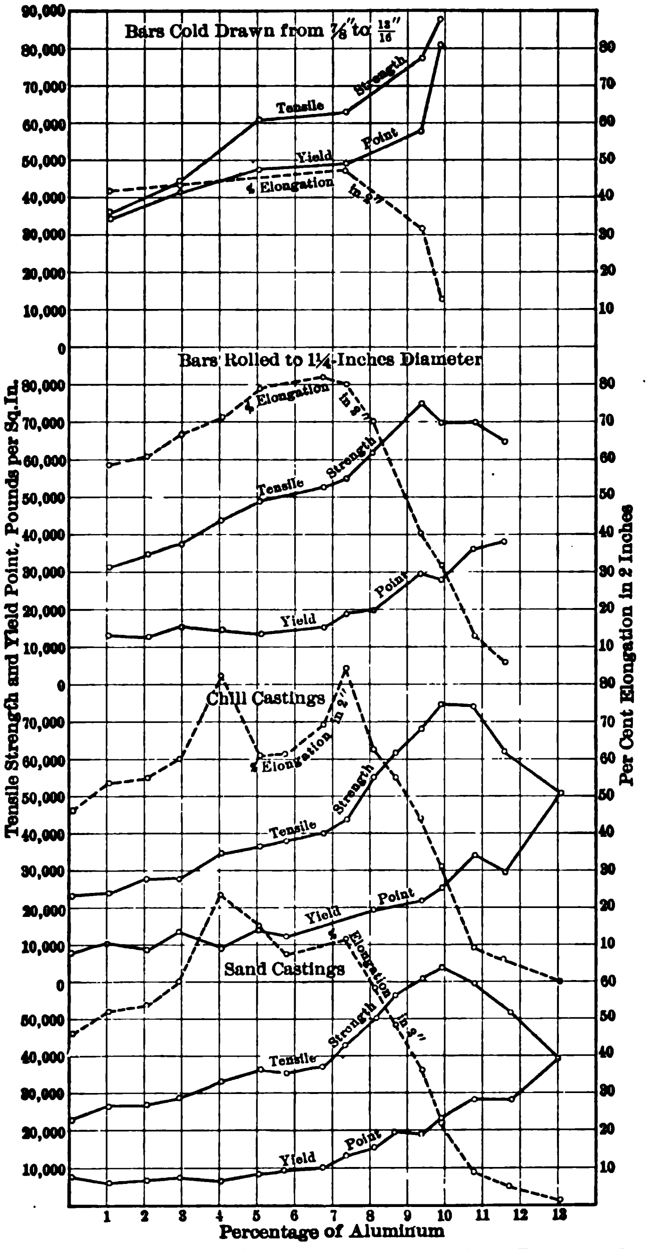

FIG. 11. — Tensile Properties of Aluminum Bronzes. (Alloys Research Committee.)

By way of summing up the discussion it may be stated that the aluminum bronzes containing less than 7.35 per cent of aluminum show moderate strength, a yield-point that is relatively low, and a ductility that is remarkably high. The high-aluminum alloys (8 to 11 per cent aluminum), show a remarkably high strength, a relatively low yield-point, and low ductility.

Most of the aluminum bronzes work well in the foundry, and may easily be rolled below a bright red heat, forged at a low red heat, or drawn into bars, shapes, sheets, tubes, wires, etc. The metal is highly resistant to corrosion and has therefore been used on marine works and as ship's fittings, including propeller blades. In ordinary machine construction and in automobile construction it has found many special uses, and, because of the peculiar smooth unctuous surface which it acquires, it has been found to be an excellent anti-friction metal. The high-copper aluminum bronze is much used as imitation gold.

32. Binary Alloys of Copper with Manganese, Phosphorus, Silicon, etc. Alloys of copper are occasionally made with manganese, phosphorus, silicon, vanadium, chromium, tungsten, antimony, bismuth, lead, arsenic, etc. None of these possess special properties which render them particularly useful commercially, and no space therefore will be devoted to a consideration of their characteristics.

ALLOYS OF ZINC, LEAD, TIN, ALUMINUM, AND NICKEL

33. Binary Alloys of Zinc. (Non-cuprous.) Zinc forms no binary alloys of commercial importance with the exception of the brasses. The character of the various other binary zinc alloys may be briefly indicated as follows:

Lead cannot readily be alloyed with zinc in a binary alloy. *Tin* may be alloyed with zinc with care, forming white metals of almost any composition. These alloys have little practical importance. Alloys of *antimony* and zinc are difficult to make, and have little value because of their brittleness and the readiness with which they are oxidized. *Bismuth* forms alloys with zinc which are extremely brittle.

34. Binary Alloys of Lead. (Non-cuprous.) *Lead-tin alloys.* Lead and tin alloy in all proportions the most important series of alloys being those used as *plumber's solder*, and which contain from 33 to 50 per cent of tin. The best solder for wiping joints in lead pipe is one containing about 2 parts of tin to 1 part of lead, but, owing to the expensiveness of tin, the content of this constituent is often reduced. The especial value of the lead-tin solders lies in the fact that the metal passes through a pasty stage in solidifying, the lead solidifying gradually before the entire mass freezes. Another alloy of lead and tin formerly much used for making various domestic utensils, slush castings, etc., is that which is called *pewter*. As tin is added to lead the latter is hardened and strengthened gradually until an alloy of maximum strength is reached with about 70 to 75 per cent of tin present. Ordinary pewter contains from 50 to 80 per cent of tin, the quality being best when the tin content exceeds 70 per cent. A little antimony or copper may be used to harden pewter.

Lead-antimony alloys. Antimony is often present in lead accidentally, as has been above noted, the resultant impure lead being known as " antimonial lead " or " hard lead " which may be used as type metal with or without the addition of tin, bismuth or copper. Antimony hardens lead very rapidly and in large amounts makes it very brittle, but at the same time forms an alloy which casts well and takes a very sharp impression of the mold. The average type metal contains about 17 per cent of antimony and may also contain from 10 to 20 per cent of tin or small amounts of bismuth, copper, etc. Lead-antimony alloys used for shot, bullets, etc., contain about 12 to 16 per cent of antimony.

Lead-bismuth alloys. Lead-bismuth alloys are easily made, so long as the proportion or bismuth is less than that of lead. The resultant alloys exceed pure lead in ductility and malleability, but have no important commercial applications.

Lead-cadmium alloys are seldom produced and possess no commercial importance.

Lead-arsenic alloys are made intentionally for only one purpose — the making of shot. The addition of from 0.5 to 1 per cent of arsenic renders the lead more fusible, lengthens the time of solidification, thus facilitating the assumption of a spherical form by the lead in its drop in the shot tower, and makes the metal, when solidified, somewhat harder than pure lead.

35. Binary Alloys of Tin. (Non-cuprous.) The principal classes of binary tin alloys have been considered above. *Cadmium* forms alloys of little practical value, and *antimony* forms alloys which are similarly without commercial importance with the exception of one alloy, known as *Brittannia metal,* which is used to a slight extent for ornamental castings and stamped or wrought forms which are usually polished or plated. The usual composition of this alloy is 80 to 90 per cent of tin and 5 to 15 per cent of antimony, the balance of the composition being made up of small amounts of copper, zinc, etc., added for the sake of their hardening effect. The binary alloys of tin with *bismuth, nickel,* etc., possess no great industrial importance. In general, none of the alloys of tin, excepting the brasses and the tin-lead alloys, possess valuable properties, and their high cost therefore bars their use where cheaper alloys will serve as well.

36. Aluminum Alloys. A great number of metals, and some non-metallic elements, are added to aluminum for the purpose of strength-

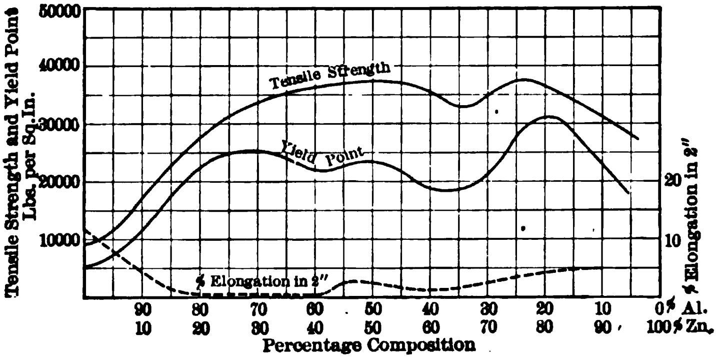

Fig. 12. — Tensile Properties of Aluminum-Zinc Sand Castings. (Alloys Research Committee.)

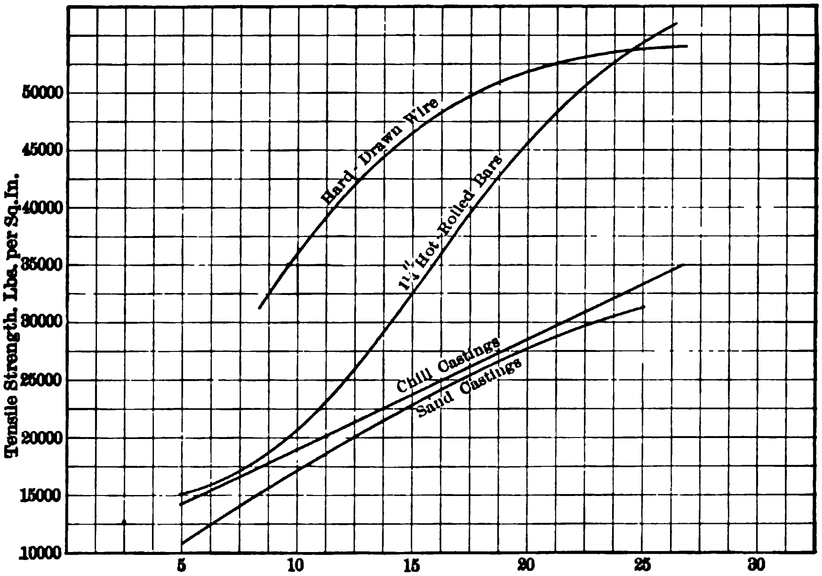

Fig. 13. — Effect of Mechanical Working on Strength of Aluminum-Zinc Alloys. (Alloys Research Committee.)

ening or hardening it, without materially increasing its weight. These alloys are generally classed as *light aluminum alloys.*

Aluminum-zinc alloys are the cheapest of the light alloys. Proportions up to about 25 per cent of zinc are used, the most ductile and malleable alloys containing less than 15 per cent of zinc, while those containing higher zinc contents are still useful in castings which permit of a certain degree of brittleness. These alloys are readily made, are harder and more fusible than aluminum, and are still very light.

The properties of the aluminum-zinc alloys have been exhaustively studied by the Alloys Research Committee* and a summary of a portion of their report is presented by Fig. 12. It is shown by the diagram that all of the alloys containing more than about 15 per cent of zinc are very non-ductile and brittle, and that even when ductility is unimportant no gain in strength, or at least in yield-point, is obtained by increasing the zinc content beyond about 30 per cent. The beneficial effect of hot and cold working of these alloys is shown by the diagram of Fig. 13.

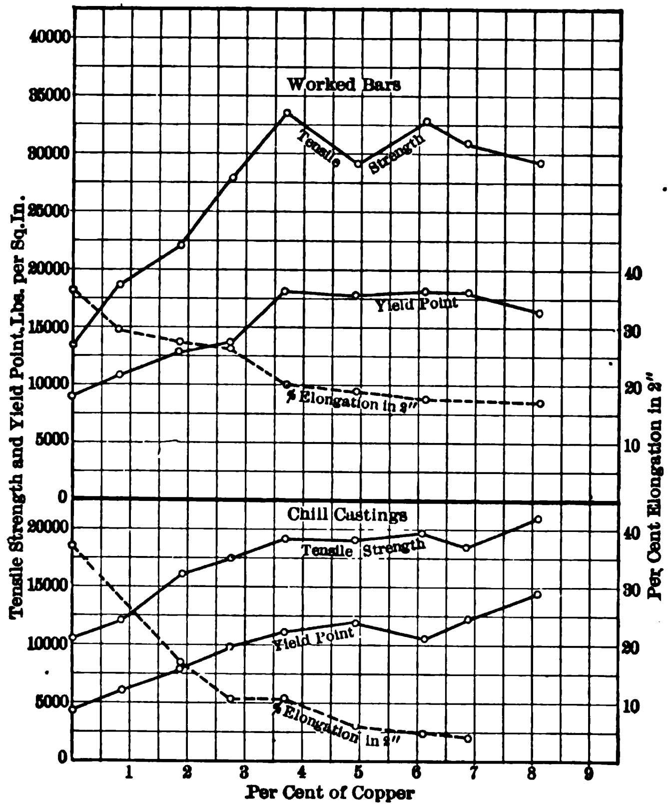

FIG. 14. — Tensile Properties of Aluminum-Copper Alloys. (Alloys Research Committee.)

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* Tenth Report, Proc. Inst. Mech. Engrs., 1912, p. 319.

Aluminum-copper alloys. Copper is one of the most commonly used hardening agents in aluminum alloys, the amount used in binary alloys rarely exceeding about 6 or possibly 8 per cent. The copper raises the strength and the yield-point considerably, but causes a rapid loss of ductility.

The properties of this series of alloys have also been studied by the Alloys Research Committee, and a portion of their report is summarized by the diagrams of Fig. 14. A comparison of this diagram with the diagrams of Figs. 12 and 13 shows that the aluminum-copper alloys are considerably inferior to the aluminum-zinc alloys in strength, but greatly excel them in ductility. The yield-point also is not relatively nor actually as high in the copper alloys as in the zinc alloys.

Aluminum-magnesium alloys. The alloy of aluminum and magnesium possessing the most valuable properties is one containing less than 2 per cent (usually about 1.6 per cent) of magnesium. This alloy is slightly lighter than pure aluminum, but shows a tensile strength of 25,000 to 40,000 pounds per square inch when cast and rapidly cooled or when rolled without annealing. The commercial alloy of aluminum and magnesium usually contains small percentages of copper, nickel, tin or lead. Mr. J. W. Richards* quotes tests of aluminum-magnesium alloys showing the following properties

	2 Per cent Mg.		4 Per cent Mg.		6 Per cent Mg	
	Tens. Str. Lbs. per Sq. in.	Per cent Elong.	Tens. Str. Lbs. per Sq. in.	Per cent Elong.	Tens. Str. Lbs. per Sq. in.	Per cent Elong.
Cast in sand	1700	3.0				
Cast in chills	28600	2.0	28600	2.6		
Castings water chilled	40000	1.0	.....	.....	57600	1.0
Annealed sheet	25600	18.0	28200	8.0	28100	17.0
Hard sheet	41300	2.7	44900	2.1	44100	1.0

	8 Per cent Mg.		10 Per cent Mg.	
	Tens. Str. Lbs. per Sq. in.	Per cent. Elong.	Tens. Str. Lbs. per Sq. in.	Per cent Elong.
Cast in sand	....	....	21400	2.4
Cast in chills	....	....	33600	3.4
Castings water chilled	54900	1.6	61100	4.2
Annealed sheet				
Hard sheet				

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* Proc. Am. Soc. Test Matrls., Vol. 3, p. 245.

Aluminum-copper-zinc alloys. Various alloys of this type contain from 9 to 27 per cent of zinc and 3 to 5 per cent of copper. The Alloys Research Committee* found the alloy containing about 25 per cent of zinc and 3 per cent of copper to possess quite valuable properties. When cast in sand or in chills it showed a tensile strength of 36,500 and 40,400 pounds per square inch, respectively, but was almost absolutely nonductile. When hot rolled, however, it developed a tensile strength of over 60,000 pounds per square inch with a yield point of about 44,000 pounds per square inch, and an elongation of about 16.5 per cent.

The rapid increase in the number of automobiles and especially the demand for light alloys for airplane construction have brought aluminum alloys into such prominence that they are approaching the copper alloys in engineering importance.

The most widely used of the casting alloys is that already mentioned as containing about 92 per cent aluminum and 8 per cent copper. This is commonly known as No. 12 or as the Society of Automotive Engineers (S. A. E.) No. 30 and has an extended use in the production of various automobile and airplane parts, crank cases, cam shaft housings, bodies and with certain slight modifications, for pistons. The aluminum alloy has the advantage of lightness and high heat conductivity and for the latter reason is especially valuable in airplane construction where cooling requirements are severe. The alloy is used to a large extent in the making of die-castings. The physical properties vary slightly with the conditions but are approximately as follows: —

	Sand cast	*Die cast*
Tensile strength lbs. per sq. in	20000	25000
Elastic limit lbs. per sq. in	13000	13000
Elongation in 2 inches	1.7%	3.1%
Specific gravity	2.84	2.8

British practice favors the addition of small percentages of tin (up to 2 per cent) to the aluminum-copper alloy for piston manufacture and alloys containing decreased quantities of copper with an addition of 2 to 15 per cent of zinc are also used.

Duralumin. The most interesting of the aluminum alloys and the ones which are most commonly used for rolling and drawing are those sold under various trade names, but all are developments of duralumin. Duralumin has remarkable properties that are not associated with any common alloy. An average analysis gives:

Aluminum	94.4 per cent.	Magnesium	0.6 per cent
Copper	4.5 per cent	Manganese	0.5 per cent

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* Appendix to Tenth Report.

Immediately after rolling the metal has a tensile strength of 30000 to 35000 lbs. per sq. in. with an elongation of about 14 per cent in 2 inches. If it is then heated to about 510° C. (950° F.) and suddenly cooled (quenched) it is soft and malleable for a very short time but soon begins to undergo a marked change in properties due to " ageing." Within 4 or 5 days after quenching the tensile strength will have increased to 50000 to 65000 pounds per square inch and the elongation to about 20 per cent in 2 inches. The alloy in the rolled and " aged " condition is remarkably resistant to corrosion and does not seem to be seriously affected by fatigue stresses. It is much used in aircraft construction and under conditions which need a material with the lightness of aluminum and almost the strength of some classes of steel. Duralumin is the alloy which has made possible the building of the large dirigibles of the Zeppelin type and in the form of rolled sheet has been used in the construction of the all-metal airplane. The tensile properties are given in the following table:*

Form	Tensile strength.	Yield point.	Elongation in 2 inches.
	Lbs. per sq. in.	Lbs. per sq. in.	Per cent.
Sheet	55000–65000	25000	15
Tubes	55000	35000	15
"	50000	25000	20
Bars ¼ to 1 inch	55000–65000	25000	15
Bars 1 to 2 inches	50000	25000	15
Bars 2 in. and above	45000	20000	15

Minor alloys of aluminum. Alloys of aluminum with nickel, tin, manganese, tungsten, chromium, titanium, silver and antimony have been made commercially, but none possess such valuable distinctive properties as to have won for them an important place among the light alloys. The commercial alloy known as " nickel aluminum alloy" usually contains only a trace of nickel, and is for the rest an alloy of 2 to 7 or 8 per cent of copper in aluminum.

552. Alloys of Nickel. German Silver. The principal nickel alloys not considered above are a large number of alloys of copper, nickel, and zinc, to which other metals are sometimes added in small amounts, and which are known collectively as *German silver.* This alloy is chiefly valuable because of its silvery white color and its non-corrodibility.

A typical composition of German silver is nickel 18 to 20 per cent, zinc 28 to 32 per cent, and copper 50 to 56 per cent. The whitest metal

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* Circular of the Bureau of Standards. No. 76.

is obtained with about 25 to 30 per cent of nickel and 20 to 25 per cent of zinc, but, since the nickel is the most expensive constituent, its proportion is often cut down. The alloy containing 30 per cent of zinc and about 18 per cent of nickel is quite white, makes smooth sound castings, and is best from the standpoint of malleability and toughness. Aluminum in amounts up to about 25 per cent makes the metal more fluid while molten and is therefore desirable in castings. It also toughens the cooled casting. Iron hardens the metal, and makes it whiter when present in amounts not exceeding 1 to 2 per cent. Tungsten up to 1 or 2 per cent is also occasionally used to form an alloy called " platinoid " which has very high electrical resistance, and is used for electrical purposes.

German silver is principally used in the making of domestic utensils, table ware, decorative objects, physical and scientific instruments, coinage, etc.

An important alloy of nickel with copper and small percentages of other elements is the so-called " natural alloy " *Monel metal,* obtained by the direct smelting of a Canadian ore in which the elements are present in approximately the following percentage relations

Nickel	67%
Copper	28%
Other metals	5%

It is chiefly of value because of its great resistance to corrosive liquids, acids, pickling solutions, mine waters and the like and because of the fact that it retains its physical properties at temperatures considerably higher than most of the common alloys both non-ferrous and steel. Its general properties are as follows: —

Melting point	1360° C. (2480° F.)
Yield point	45000–63000 lbs. per sq. in.
Tensile strength	85000–95000 lbs. per sq. in.
Elongation	44% to 32% in 2 inches.

553. Special Bearing or Anti-friction Metals. The bearing bronzes and the lead-antimony bearing metals have been considered above. Aside from the bearing bronzes, the best-known bearing metals are those composed of tin, copper, and antimony which are known as *Babbitt metal.* The composition of this alloy is extremely variable, but the usual limits are tin 80 to 90 per cent, copper 3 to 10 per cent, and antimony 8 to 12 per cent. The quantity of antimony should always exceed the amount of copper in order to prevent brittleness. The ultimate constitution of Babbitt metals appears to be that of a ground mass of soft tin with hard crystals of a copper-antimony compound and a tin-antimony compound scattered through it. The hard particles carry the load and resist wear, while the soft ground mass allows the metal to adjust itself to the surface of the shaft and equalize the bearing pressure.

Alloys of lead, tin, and antimony have been considerably used as bearing metals, the best compositions being those containing 10 to 15 per cent of antimony, 10 to 20 per cent of tin, and the balance lead.

Alloys of lead, copper, and antimony have occasionally been used as bearing metals where heavy loads are encountered. A typical composition is 65 per cent of lead, 10 per cent of copper, and 25 per cent of antimony.

Alloys of zinc, tin, and antimony, and *alloys of lead, tin, and bismuth*, have been used as bearing metals, but their general application has been very limited on account of a tendency toward fragility on the part of the former, and the high cost of bismuth in the case of the latter.

Alloys of lead with barium or with *calcium* have recently been used with considerable success as bearing alloys.

SECTION 7

CHAPTER I

TIMBER *

1. General. Timber has been one of the primary materials of engineering construction since the earliest times, and, despite the fact that it has been largely superseded by concrete and steel in certain classes of structures, the total consumption of timber for structural and other commercial purposes is steadily increasing.

In spite of the great number of species of trees (something like 500 grow in the United States alone), only a very limited number of kinds of timber are of great commercial importance, the larger part of all timber used structurally being derived from only twelve distinct species of trees — those commonly known as *pine*, *fir*, *oak*, *hickory*, *hemlock*, *ash*, *poplar*, *maple*, *cypress*, *spruce*, *cedar*, and *walnut*. These common names of species usually include several varieties, which may show quite diverse characteristics and possess, therefore, very different values as timbers of construction.

Much confusion exists as to the common nomenclature of woods, the same species or variety being known by many different local names, and different species are sometimes known in different localities by the same name. The recognized botanical Latin nomenclature affords a dependable guide to species, but is too cumbersome for general use. In consequence, various national societies like the American Society for Testing Materials and the American Railway Engineering and Maintenance of Way Association have adopted standard classifications of the structural timbers used commercially, listing the various common names of a given species under a single name whose meaning is thus defined.

Any study of the characteristics and properties of woods must include some information concerning trees. The point of view of the engineer need not be that of the botanist, and his study may be confined to the general features, conditions and manner of growth of a limited number

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* The data upon which this chapter is based is taken, very largely, from the publications of the U. S. Forest Service and the text-books of Record and Betts.

of species of trees, but physical and mechanical properties of timbers are closely dependent upon structure, and structure is not only dependent upon variety, species, and genus, but within a given variety, upon conditions of growth — climatic and soil conditions. No detailed botanical consideration of trees will be included herein, but a general classification of trees will be made, together with some study of growth and structure.

TIMBER WOODS. GROWTH AND STRUCTURAL CHARACTERISTICS

2. Classes of Trees. All trees are primarily divided into two botanical groups according to their manner of growth:

Exogenous trees, or *exogens*, increase in diameter by the formation between the old wood and the bark of consecutive rings or layers of new wood which envelops the entire living portion of the tree. Practically all classes of commercially important timbers are derived from trees of this group.

Endogenous trees, or *endogens*, grow both diametrically and longitudinally, principally the latter, by the addition of new wood fibre intermingling with the old. Most endogens are small plants like corn, sugarcane, wheat, rye, etc., but others like the palm, the yuccas and the bamboo have some value as a source of structural material.

Exogenous Trees

3. Conifers. *Conifers*, the needle-leaved, naked-seeded trees, form the most important portion of our timber trees, comprising principally the pines, the spruces, fir, hemlock, larch, tamarack, cedar, cypress, and redwood. They are usually light and soft, hence often called "soft woods." The trees may invariably be recognized by their needle leaves, their resinous bark and the cones which they bear. They are for the most part "evergreens."

4. Broadleaf Trees. *Broadleaved* trees provide a source of timber second in importance only to the conifers. They comprise many varieties of oak, ash, hickory, poplar (cottonwood), maple, walnut, elm, chestnut, birch, beech, cherry, locust, basswood (linden), whitewood (tulip), sycamore, catalpa, butternut, buckeye, alder, willow, eucalyptus, gum, horsechestnut, holly, boxwood, laurel, lignum-vitæ, mahogany, satinwood, and many other species of lesser commercial importance. They are usually heavy and hard, hence often called "hard woods," and, as a rule, they are deciduous, although many broadleaf trees are evergreen in certain climates. The broadleaf woods are not used for structural purposes to anywhere near the same extent as the conifers, but are specially adapted to use for interior finishing, cabinet work, furniture, etc.

ENDOGENOUS TREES

5. Endogenous Trees. This group is confined largely to tropical or semi-tropical regions. The palms, because of their long straight stems and comparative immunity from the destructive action of the teredo (a form of marine wood-borer which is very active in some waters), are sometimes locally used as piles, but have practically no other commercial uses. Only a few varieties are native to the United States. The yuccas find little application to commercial uses except as paper-pulp and as a veneer adapted to certain special uses where its lightness and flexibility are advantageous. The bamboo is not native to the United States and, where found, has been transplanted from Asia. The bamboo grows with extreme rapidity, but requires years to harden after its growth is attained. Bamboo has many commercial uses in Asia, particularly in Japan and in China, where it is even used structurally to a considerable extent.

EXOGENOUS GROWTH OF WOOD *

6. Pith, Wood, and Bark. The section of any exogenous tree exhibits first a central portion composed of loosely aggregated thin-walled cells called the pith. It is black, red brown, or gray in color; usually of small diameter, and does not increase in size after the first year. Often the pith becomes compressed and is sometimes scarcely evident in sections of mature trees.

Outside the pith the wood appears in concentric zones or rings of annual growth, the demarkation between which is evident because of the different structure of the wood slowly formed toward the end of one season and that rapidly formed in the succeeding spring.

The outermost portion or periphery of the section is formed by material of variable and very complex structure called the bark. The bark of many trees possesses a distinct commercial value. Many trees furnish bark for medicinal purposes, others, like the hemlocks and the oaks, supply a great part of the tannin used in the leather industries, several serve as a source of coloring matter, others furnish fiber for cloth and cordage, and one particular species provides the cork of commerce.

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* For a much more detailed treatment of the growth and structural elements of wood see Record's "Economic Woods of the United States," "Plant Anatomy" (Stevens) "Handbook of Trees of the Northern States and Canada" (Hough), "Wood and Other Organic Structural Materials" (Snow).

7. Wood Structure. Wood being the result of the development and growth of an organism well up on the scale of vegetable life, it is only to be expected that the cell structure will present some degree of variation and complexity. It is by no means the province of this book to enter into those details, which, however significant to the naturalist, have little bearing on the engineering aspect of this material. Intelligent use of timber does, however, necessitate some knowledge of its cell structure. Those peculiarities of structure which directly affect its strength, durability, behavior during seasoning and susceptibility to preservative treatment will consequently be briefly outlined in the following paragraphs.

In the broadest interpretation wood may be considered to be made up of two chief structural elements, *cells* and *vessels*. The elemental *cells* are technically subdivided as *tracheids*, *wood fibres* and *parenchyma* (called resin cells in the wood of the conifers). While it is true that there is considerable difference in form and function between these various subdivisions, such distinctions are beyond the scope of this discussion and all of these elements will be here referred to simply as cells. In cross-section these cells are roughly polygonal and most commonly appear to be rectangular with rounded corners, as will be noted

Fig. 1. — Cross-section of Diffuse-Porous Wood. (Hard Maple.) (Bull. 126, U. S. For. Ser.)

Fig. 2. — Cross-section of Ring-Porous Wood. (Red Oak.) (Bull. 126, U. S. For. Ser.)

by reference to the various figures. The cells are closed at the ends and may vary from 0.02 to 0.2 inch in length. Their diameter will generally be less than 0.002 inch. The *vessels* are formed by the fusion of numbers of cells and are in the form of open tubes often extending the entire length of the tree. They are usually large enough to be perceived in the cross section of wood with the unaided eye, sometimes attaining 0.03 inch in diameter. The absence or arrangement of these vessels gives rise to a rough classification of wood into three divisions; namely "Diffuse porous," Fig. 1, "Ring porous," Fig. 2, and "Non-porous," Fig. 3. In the non-porous woods (conifers in general) there appear tubular spaces between the cells, called "Resin ducts." These differ from the vessels of the porous woods in that they possess no true walls, Fig. 4.

Fig. 3. — Transverse Section of Norway Pine. Magnified 25 Diameters. (Bull. 139, U. S. For. Ser.)

e.w., early wood; *l.w.*, late wood; *t.*, tracheids; *p.r.*, pith ray; *r.c.*, resin canal.

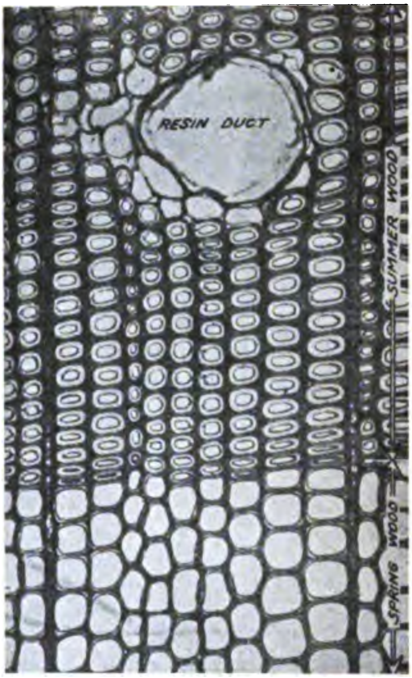

Fig. 4. — Transverse Section of Shortleaf Pine, Showing Resin Duct. (Magnification 125 diameters.) (Bull. 101, U. S. For. Ser.)

All of the elements above referred to are arranged with their longitudinal axes approximately parallel with the axis of the tree or branch in which they lie. There are other and very important cells which are arranged in bundles with their long axes commonly perpendicular to the axis of tree or branch. These radial series of cells are known as "*pith* or *medullary rays*." Such rays are continuous from their point of origin to the bark. A cross-section of these rays, Figs. 5, 6, and 7, shows them to consist of from a very few cells to several hundred, depending upon the kind of wood. The medullary rays in some woods such as oak are frequently of very great vertical dimensions, and it is to them that "quarter sawed oak " owes its beautiful figure.

FIG. 5. — Tangential Section of Circassian Walnut. (Cir. 212, U. S. For. Ser.)

v, vessel; *p.r.*, pith ray; *w.f.*, wood fibres; *w.p.f.*, wood-parenchyma fibres; *c.w.*, cross wall; *b.p.*, bordered pits. Magnified 30 diameters.

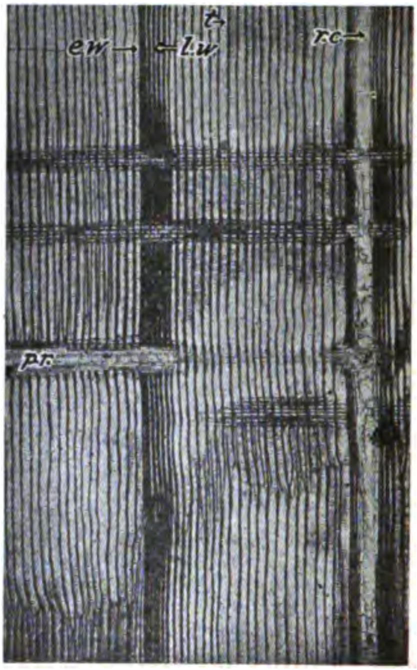

FIG. 6. — Radial Section of Norway Pine. Magnification 25 Diameters. (Bull. 139, U. S. For. Ser.)

e.w., early wood; *l.w.*, late wood; *t.*, tracheids; *p.r.*, pith ray; *r.c.*, resin canal in pith ray; also a longitudinal canal.

8. Annual Growth Rings. Spring and Summer Wood. The growth of all exogenous trees is a process of formation of new wood fibre between the old wood and the inner bark. Owing to the inability of trees to sustain their physiological activities indefinitely, and the effect of the alternation of seasons in all temperate zones, this growth is intermittent, and the zones of growth correspond to the annual periods. The succeeding rings of growth may easily be distinguished from one another in most species because of the different structure of the wood formed rapidly in the spring and that more slowly added in the summer. (Fig. 8.) No wood is added during the winter months. The distinction between adjoining growth rings is sometimes augmented by the deposition of infiltrated pigments or resin in the late wood. Thus it happens that the age of most trees may be accurately determined by counting the annual rings on a section of the stem.

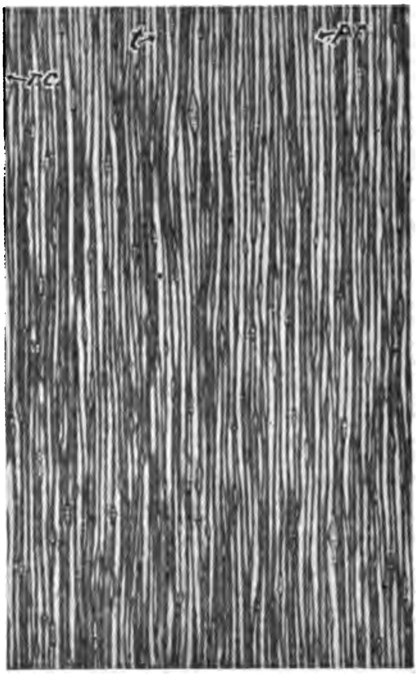

FIG. 7.—Tangential Section of Norway Pine. Magnification 25 Diameters. (Bull. 139, U. S. For. Ser.)

t., tracheids; *p.r.*, pith rays; *r.c.*, resin canal in pith ray.

The difference in appearance between the spring wood and the summer wood is occasionally so marked as to make the two appear as distinct bands within a single annual ring (the spring wood is comparatively light colored and the summer wood dark colored) as in the species commonly called, collectively, hard or yellow pine. More commonly, however, the spring wood merges gradually into the summer wood, and the only sharp line of demarkation is between the summer wood of one season and the spring wood of the following season, as is the case with the spruces. The structural difference between spring wood and summer wood may consist (1), in either an abrupt or gradual reduction in the number or the size of vessels in the later wood, e.g., oaks, chestnut, ash, locust, etc., which are called "ring porous," Fig. 2, while other broad-leaved woods like maple, walnut, beech, birch, etc., show only a gradual change and are called "diffuse porous," Fig. 1; (2) in a change in the kind of wood elements, e.g., where vessels are absent from the later wood, being replaced by wood parenchyma or tracheids; or, (3) where the cell walls of the various wood elements become thicker as the season progresses, the lumen becoming correspondingly smaller and the wood more dense. This structure is characteristic of white pine, spruce, etc., Fig. 3.

FIG. 8. — Transverse Section of the Stem of a Young Balsam Fir Tree, Showing Annual Rings of Growth, *a.r.*, ½ Natural Size. (Bull. 55, U. S. For. Ser.)

It is a commonly observed fact that the rate of growth of trees is quite variable, not only in different species, but even for different specimens of the same species. This means that the growth rings are of variable thickness. When the conditions of soil, light, heat, moisture, etc., are such as to produce normal thrifty growth, the width of the rings is greatest near the pith, decreasing outward, and it is also normally greater at the base of the stem, decreasing upward. Unfavorable soil or climatic conditions, or unfavorable seasons, will disturb the normal regularity of growth, however, and the cross-section of the stem therefore presents a history of the growth in succeeding favorable and unfavorable seasons. The thickness of the ring is not even uniform circumferentially, because of unequal acceleration of the growth on different sides; thus the section often becomes oval and, even if circular, the pith is eccentric (Fig. 8).

The maximum thickness of growth rings attained during the period of thriftiest growth rarely exceeds 0.5 inch for either conifers or broad-leaved trees. For most trees a thickness of 0.10 inch to 0.15 inch indicates a good thrifty growth, and, for trees grown under unfavorable conditions, as well as for the outer wood of very old trees the ring thickness may not exceed 0.005 inch to 0.02 inch. Trees grown in dense forests always grow less rapidly than trees grown in the open, and the growth is likely to be less rapid (the rings thinner) at the base of the stem than farther up. (Note that this is a reversal of the normal habit of growth.)

In most of the conifers the distinction between spring wood and summer wood is due to a thickening of the walls of the tracheid cells and a flattening of the cells radially, resulting in a greater density in the summer wood. The proportion of summer wood in a growth ring is normally least in the wood of the sapling, greatest in the intermediate period of thrifty growth of the tree, and falls below the average again in old age. It should average 40 to 50 per cent of the wood near the base of the stem, and falls slightly below this average at the base of the limbs. The proportion of summer wood largely determines the density, strength, and structural value of the wood, and together with rate of growth is now used as a very important basis for the grading of structural timber.*

In most of the broad-leaved trees the distinction between spring and summer wood is largely due to a diminishing in the space occupied by vessels, and the summer wood is again the denser, heavier, and stronger portion of the wood. Unlike most coniferous woods, however, the ring-porous broad-leaved woods form their densest and strongest wood during the period of most rapid growth. This fact is due to a difference in character of the wood elements formed under different conditions of growth. When growth is most rapid, and the rings therefore widest, the middle portion of each ring contains a great abundance of the thick-walled, strong, and tough wood fibres. When the rings become narrower, it is at the expense of these wood fibres, whose strength-giving qualities cannot be equaled by the thin-walled vessels and parenchyma present. This accounts for the general preference for "second-growth" hickory, ash, etc., which has grown in less dense forest than the virgin timber, and whose growth has therefore been more rapid.

9. Sapwood and Heartwood. As the process of formation of annual rings of new wood adds layer after layer of vigorous healthy tissue over that previously formed, the latter gradually ceases to take an active part in the physiological activities of the tree, loses its protoplastic contents, and dies. Decay does not usually follow immediately, however, and the dead wood continues sound and provides mechanical support for the tree.

The living elements of the tree are called "sapwood" and the dead elements "heartwood." There is usually a sharp line of demarkation between the sapwood and heartwood, although the vigor of the living wood decreases progressively from the cambium inward. The proportion of sapwood varies considerably in different species and also between individuals of the same species. Certain woods, such as maple, ash, beech, hickory, etc., usually form thick sapwood, while the juniper, the catalpa,

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* The southern pines are no longer graded according to species, but in accordance with the "density rule" in brief as follows. "Dense southern yellow pine shall show on either end an average of at least six annual rings per inch and at least one third summer wood . . . as measured over the third, fourth, and fifth inches on a radial line from the pith. Wide ringed material excluded by this rule will be acceptable, provided that the amount of summer wood as above measured shall be at least one-half." (A.S.T.M. definitions D 9–15.)

the locust, the yew, and many others, normally form thin sapwood. Since the sapwood zone is the outer one, it forms a considerable percentage of the volume of the wood. The normal percentage of sapwood in the hickory, for instance, is about 75 per cent; in the maple, ash, beech, etc., it exceeds 50 per cent; while in the juniper, catalpa, yew, etc., it does not usually exceed 25 per cent, and in the case of the locust may not amount to more than 15 per cent. Within the same tree the percentage of sapwood usually decreases from the base upward and is least in the branches. All young trees show a higher percentage of sapwood than do old trees of the same species.

The distinction in color between sapwood and heartwood, which is characteristic of most woods, is due to the darkening of the dead wood by the presence of infiltrated pigment, gums, resins, etc., which permeate the cell walls and sometimes also the cellular and intercellular cavities. Certain woods, like spruce, fir, hemlock, poplar, willow, gum, etc., show little or no difference in appearance between the two portions.

As a rule, the heartwood is more highly valued than the sapwood of the same variety. This is due to the fact that the heartwood offers greater resistance to decay than does the sapwood. In so far as strength is concerned, the prejudice in favor of the heartwood is entirely without justification, since the sapwood except in very old trees is the equal to the adjoining heartwood in strength. There are, however, noteworthy instances in which the sapwood is preferable, as, for example, hickory, ash, birch, all the paper pulp woods, and timber to be treated with preservatives.

ENDOGENOUS GROWTH OF WOOD

10. Endogenous Growth. Any detailed consideration of the growth and structure of endogens is not justified, because of the relative economic unimportance of trees of this class as sources of structural timber.

The elements of the wood of endogens are similar to those of exogens, but their disposition and arrangement are radically different. The vascular bundles found in endogens are not grouped in concentric circles, but are scattered throughout the volume of the wood, each one being isolated from neighboring ones by thin-walled tracheary cells which form a pith which offers little resistance to the growth of the bundles. The bundles are not even parallel to the stem in most cases, but each one curves inward in a vertical plane (from the point where it entered a leaf), and then outward again, thus crossing many other bundles and making the structure more complex. Usually the development of new tissue is more rapid at the periphery and in the outer zone of the stem than in the interior. This results in the production of much more dense tissue toward the exterior, the solidity of the wood decreasing from the circumference toward the center. Often, when the growth is very rapid, sluggishness on the part of the interior fibre causes it to become ruptured and the enlargement of the cavity finally produces the hollow stem characteristic of the bamboo and many grasses, but not of the palms, yuccas, etc., which have a pithy center. The occurrence of knots or joints at frequent intervals is common to many endogens, particularly those which form a hollow stem. The knots mark the places whence leaves have emerged.

PHYSICAL CHARACTERISTICS OF WOOD

11. Grain and Texture of Wood. The physical appearance of wood, so far as that is dependent upon the character and arrangement of wood elements, the width of the growth rings, etc., is described by the common terms "fine grained" and "coarse grained," "even," "smooth," or "straight grained," and "uneven," "twisted," or "cross grained," and, in a few instances, by the less common terms "curly," "mottled," "bird's-eye," etc. Woods are *fine grained* if the growth has been slow, resulting in narrow rings; *coarse grained* if the rings are wide. If the main wood elements of a tree run parallel to its axis the log will be *straight grained;* often, however, the fibres follow a spiral course around the tree, producing a log of *twisted grain.* Sometimes the fibres may be oblique in one direction for several years' growth, and then become oblique in the opposite direction for a time, producing a log of *cross-grained* timber. When a straight-grained log is sawn, either straight-grained or cross-grained timber may be obtained, depending upon the parallelism of the plane of cutting and the axis of the log. Straight-grained lumber may be obtained from a log of twisted or cross grain only by splitting, lumber cut parallel to the axis being inevitably cross grained.

When the layer of wood newly formed beneath the bark becomes pitted or marked by prominences, due perhaps to the presence of dormant buds, these depressions or elevations may persist for several years, resulting in the production of the beautiful effects known as "bird's-eye" marking when boards or veneer are cut tangentially. The maple has a special tendency to preserve the contour of the growth rings for many years, and bird's-eye markings and curly grain are more often encountered in maple wood than in most other woods, wherein the tendency to compensate for inequalities is strong and accidental elevations or depressions in the growth rings do not persist more than two years.

The term "texture" as applied to woods refers to the size, character, and arrangement of the wood elements in so far as they affect the structural characteristics of the wood. *Coarse texture* and *fine texture* are terms applied to woods having many large elements (particularly if many large pores are present), and to woods wherein the opposite condition prevails, respectively. The texture is *even*, or *uniform*, if the wood elements show little variation in size, and *uneven* if the contrary is true.

Knots originate in the timber cut from the stem or branches of a tree because of the encasement of a limb, either living or dead, by the successive annual layers of wood. Most limbs originate at the pith of the stem, and the knots found deep in a log are therefore small, increasing in size toward the bark. So long as the limb is growing, its layers of wood are a continuation of those of the stem. But a majority of the limbs die after a time, and, if a portion of a dead limb is subsequently encased by the growing stem, there will be no intimate connection between the new stem wood and the dead wood of the limb, and a board so cut as to intercept this portion of the log will contain a *loose knot*. A board cut from the log at such a depth that the limb is intercepted at a point where it was encased while still living will contain a *sound knot*, unless the knot has rotted, become badly checked, or contains a large pith cavity. A sound knot is usually harder than the surrounding wood and in coniferous woods is apt to be very resinous. On this account it may constitute a defect because of its non-retentivity of varnish or paint. Otherwise it constitutes a defect only on account of the disturbance to the grain and difficulty caused in working, or, in the event of its occurrence on the under side of a timber used as a beam, a weak point exists owing to its small resistance to tensile stress. A knot constitutes an impedance to the splitting of timber, since the fibres of the stem wood above a limb bend aside and pass around the limb while the fibres below run continuously into the limb. Thus it happens that a cleft started above a limb will never run into a knot, but one started below is very likely to do so.

12. Density and Weight. The density of woods of different species, different individuals of the same species, and even portions of the same individual, vary considerably, owing to differences in structure (particularly differences in the average thickness of cell walls), and to differences in the amount of water present in the cells and cell walls. The specific gravity of the ultimate wood fibre of all species, however, is about 1.6, so that it is apparent that no wood would float in water were it not for the buoyancy of the air present in the cells, walls, and intercellular spaces.

In all varieties of trees the sapwood is heavier than the heartwood, when cut, because of its greater water content, and the summer wood is heavier than the spring wood because of the smaller lumen and thicker walls of the cells of the late wood. A fibre from the dense summer wood of such a tree as the long-leaf pine will not float, regardless of its water content, and many woods will not float while still very green. Even seasoned timber of many species may be made to become "water-logged," i.e., a large part of the imprisoned air displaced by water.

Within a single tree of a given species specimens taken from different portions of the stem and branches exhibit wide variation in weight. All trees form their heaviest wood at the butt and at the base of the limb (knots), and the weight decreases toward the upper portion of the stem and the tips of the branches. Two factors chiefly influence the weight of wood formed at succeeding periods of growth: first, the proportion of summer wood formed, and second, the size and number of pores present in the early wood. The first is the controlling factor in the case of most conifers, and such trees as pine, spruce, etc., form light wood as saplings when the proportion of early wood is greatest, the heaviest wood during the period of thriftiest growth when summer wood preponderates, and lighter wood again in old age when the proportion of summer wood drops below the maximum. In most broad-leaved trees, on the other hand, especially those whose pores are conspicuous, like the oak, chestnut, ash, etc., the heaviest wood is that of the sapling and the wood becomes slightly lighter with each succeeding year's growth. This is due to the fact that the pores in the wood near the pith are very minute, but larger and larger pores are formed during succeeding periods of growth.

The weight of wood is in itself an important quality in many of its structural uses. Weight is also closely related to strength, provided the disturbing factor of variation in moisture content is eliminated.

The weight of wood is experimentally determined by subjecting thin discs of the wood to an oven temperature of 100° C. (212° F.) till they cease to lose weight by evaporation of moisture.

The following table, abstracted from the Tenth Census of the United States, gives an approximate idea of the relative specific gravity and weight of fifty of our most important lumber woods. The limited application of these average values should be remembered, and their use confined largely to the comparison of particular specimens of equal moisture content, and to a general classification of woods as very heavy, heavy, medium, light, and very light. The weight classification here given is that adopted by Roth.*

13. Moisture Content of Wood. Water occurs in the sapwood of living trees in three states: (1) It forms more than 90 per cent of the protoplasmic contents of the living cells, (2) it saturates the cell walls, (3) it partially or entirely fills the lumina of empty lifeless cells. fibres and vessels.

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* Bulletin 10, Forestry Division, U. S. Department of Agriculture.

FIFTY TREES OF THE UNITED STATES, ARRANGED IN ORDER OF AVERAGE SPECIFIC GRAVITY

(Abstract from 10th U. S. Census)

Common Name.	Gen. Class.	Approx. Sp. Gr.	Approx. Wt. Lbs. per Cu. Ft.	Wt. Class.
Lignum vitæ	Broad leaf	1.14	71	Very heavy
Live oak	"	0.95	59	"
White hickory	"	0.84	52	"
Pignut hickory	"	0.82	51	"
Osage orange	"	0.77	48	"
Cuban pine	Conifer	0.75	47	"
White oak	Broad leaf	0.75	47	"
Locust	"	0.73	46	"
Blue beech	"	0.73	46	"
Mahogany	"	0.73	46	"
Cedar elm	"	0.72	45	"
Blue ash	"	0.72	45	"
Pecan hickory	"	0.72	45	"
Long-leaf pine	Conifer	0.70	44	"
Slippery elm	Broad leaf	0.70	44	"
Sugar maple	"	0.69	43	Heavy
Beech	"	0.69	43	"
Yellow birch	"	0.66	41	"
White ash	"	0.65	40	"
Red oak	"	0.65	40	"
White elm	"	0.65	40	"
Red ash	"	0.63	39	"
Tamarack	Conifer	0.62	39	"
Black walnut	Broad leaf	0.61	38	"
Short-leaf pine	Conifer	0.61	38	"
Paper birch	Broad leaf	0.60	37	"
Sweet gum	"	0.59	37	Medium
Western juniper	Conifer	0.58	36	"
White birch	Broad leaf	0.58	36	"
Sycamore	"	0.57	36	"
Loblolly pine	Conifer	0.54	34	"
Douglas spruce	"	0.52	32	"
Red juniper	"	0.49	31	"
Bull pine	"	0.47	29	Light
Red fir	"	0.47	29	"
Black spruce	"	0.46	29	"
Bald cypress	"	0.45	28	"
Basswood	Broad leaf	0.45	28	"
Chestnut	"	0.45	28	"
Catalpa	"	0.45	28	"
White basswood	"	0.43	27	"
Hemlock	Conifer	0.42	26	"
Redwood	"	0.42	26	"
Butternut	Broad leaf	0.41	26	"
White spruce	Conifer	0.41	26	"
Incense cedar	"	0.40	25	"
White pine	"	0.38	24	Very light
Balsam fir	"	0.38	24	"
White fir	"	0.36	22	"
Cork wood	Broad leaf	0.21	13	"

The highest percentage of water is found in the wood near the bark, decreasing gradually toward the pith unless heartwood is formed, in which latter event, an abrupt decrease in the moisture percentage occurs at the heartwood limit. From the above considerations it will be apparent that, in the case of trees which do form heartwood, the moisture content at any section will vary with the proportion of sapwood, and is therefore greater in the upper than in the lower portion of the stem, still greater in the limbs, and greatest of all in the roots.

For practical purposes, wood is considered thoroughly dry when a thin cross-sectional disc or a small quantity of chips ceases to lose weight in a constant temperature of 100° C. (212° F.). At higher temperatures additional water will be given off, but chemical destruction sets in before all the water is removed.

14. Seasoning of Timber.[*] The seasoning or drying of timber necessarily precedes its application to structural purposes. The natural drying of timber by long outdoor exposure to the action of the air is called "seasoning," while artificial drying by exposure for a limited period to high temperatures in a closed chamber is called "kiln-drying." In either event the loss of moisture is entirely by evaporation, and the treatment, if properly carried out, is appreciably beneficial to strength, stiffness, and durability.

The rate of drying of timber depends upon the dimensions of the piece and the structure of the wood. Thin boards dry much more rapidly than thick planks or heavy timber, and light porous woods much more rapidly than heavy dense woods. Numerous experiments made by Mr. H. S. Betts of the U. S. Forest Service upon large timbers of loblolly and long-leaf pine established the following conclusions:[†]

"(1) The drying-out process takes place almost wholly through the faces of the beams and not longitudinally, except near the ends.

"(2) The rate of evaporation through a surface is proportional to the rate of growth or density of the wood near the surface, being most rapid in case of the sapwood.

"(3) If the whole stick is made up of heartwood or the proportion of sapwood is uniform throughout, the longitudinal distribution of moisture is very regular. If the proportion of sapwood is not uniform, on the other hand, the portion containing the most sap is the most susceptible to moisture influences, i.e., it will dry or will absorb the moisture the most rapidly.

"The average of two cross-sections of long-leaf pine sticks, 12 by

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[*] A more detailed discussion will be found in "Seasoning of Wood," J. B. Wagner, and "Timber, Its Strength and Seasoning," H. S. Betts.

[†] Bulletin 70, U. S. Forest Service, p. 123.

12 inches and 8 by 16 inches, and 16 feet long, which were air dried for two years, showed an average moisture content in the outer portion, cut half way from surface to center, of 17.7 per cent, while the inner part contained 25.7 per cent.

"From this it is quite evident that where timber of structural sizes is used, the strength ordinarily reckoned upon should not be greater than that of the green condition."

In artificial drying temperatures of 158° to 180° F., (70° to 82° C.) are usually employed.* Pine, spruce, cypress, cedar, etc., are dried fresh from the saw, allowing four days for 1-inch boards. Hard woods, especially oak, ash, maple, birch, sycamore, etc., are air seasoned for three to six months to allow the first shrinkage to take place more gradually, and are then exposed to the above temperatures in the kiln for about six to ten days for 1-inch lumber. Freshly cut poplar and cottonwood are often dried directly in kilns.

By employing lower temperatures, 100° to 120° F., (38° to 49° C.) green oak, ash, etc., can be seasoned in dry kilns without danger to the material. Steaming the lumber is commonly resorted to in order to prevent checking and case hardening. Yard-dried lumber is not dry, and its moisture is too unevenly distributed to insure good behavior after manufacture. Careful piling of the lumber, both in the yard and kiln, is essential to good drying. Piling boards on edge or standing them on end is believed to hasten drying. This is true only because in either case the air can circulate more freely around them than when they are piled in the ordinary way. Boards on end dry unequally — the upper half dries much faster than the lower half and horizontal piling is, therefore, preferable.

15. Shrinkage, Warping and Checking in Drying. The shrinkage of wood in drying is due solely to the loss of moisture from the walls of the cells. Variation in the water content of the lumina of the lifeless cells, and in the protoplasmic contents of the living cells, does not affect the volume of the wood in any way.

As moisture is evaporated, the cell walls become thinner; the lumina become larger, and the exterior cross-sectional dimensions become smaller. The contraction of a wood element in a longitudinal direction is scarcely appreciable, however. The total volumetric change of an element is roughly proportional to the original thickness of its walls. The aggregate volumetric change of a mass of thin-walled wood elements is therefore much less than that of a mass of thick-walled elements, Fig. 9. This explains the fact that summer wood almost invariably shrinks more than spring wood, its wood elements being thicker walled, and dense wood shrinks more than lighter wood of the same species for the same reason.

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* Roth, Bulletin 10.

Irregularities in the structure of all wood prevents shrinkage being uniform throughout. The rays, whose elements are for the most part arranged at right angles to the main wood elements, oppose shrinkage in a radial direction and tend to cause longitudinal shrinkage. The bands of dense summer wood are continuous in a tangential direction, but in a radial direction they alternate with less dense spring wood. On this account tangential shrinkage commonly amounts to at least twice the radial shrinkage. Longitudinal shrinkage will be greatest in woods having an abundance of large rays or those exhibiting wavy or spiral grain (the lack of parallelism of the wood elements with the pith in this case being accountable for the existence of a component of the transverse cell shrinkage in a direction parallel to the pith), but in any event the longitudinal shrinkage amounts to only a few tenths of 1 per cent.

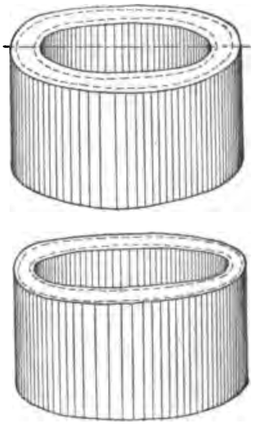

FIG. 9. — Shrinkage of thick-walled and thin-walled fibres. (Bull. 10, U. S. For. Div.)

The warping of lumber is due either to unequal drying of different portions, or to unequal shrinkage on account of irregularities in structure. Any straight-grained green board exposed on one side only to air and heat will become concave on the exposed side because of the more rapid drying and consequent shrinkage of that side. Boards cut tangentially from the log tend to become convex on the side toward the pith when dried, because of the greater shrinkage of the wood in a direction parallel to the annual growth rings. Each growth ring tends to shorten, thus causing the edges of the board to curl away from the pith as shown by Figs. 10 and 11. If lumber is cross-grained, the component of the shrinkage in a longitudinal direction causes a warping lengthwise as well as in the transverse direction, and where the grain is spiral boards may become badly twisted. Warping is always more likely to be encountered in the lumber from woods of great irregularity. Serious deformation of such lumber can be avoided only by most careful handling in drying.

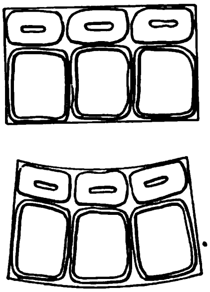

FIG. 10. — Shrinkage of Thick- and Thin-walled Fibres. Warping of Wood. (Bull. 10, U. S. For. Ser.)

Checking of timber in drying is a consequence of the inability of the wood to accommodate strains consequent upon unequal shrinkage. A great many small checks occur, particularly in the ends of timbers, owing to the more rapid drying from the cross-section and the consequent excess of shrinkage of the end portion over that of the balance of the timber. This results in a tendency to bend the fibres, Fig. 12, and their stiffness may be sufficient to cause rupture between strands, thus relieving the stress. Similar checks occur on the sides of logs and timbers because of the precedence of the shrinkage of the outer portion over that of the inner portion, which has scarcely begun to lose its moisture. Both of these classes of seasoning checks are considered temporary, because they close up and become imperceptible as the inner portion of the timber dries and shrinks. They are still there, whether visible or not, however, and always impair the structural qualities of the wood in some measure.

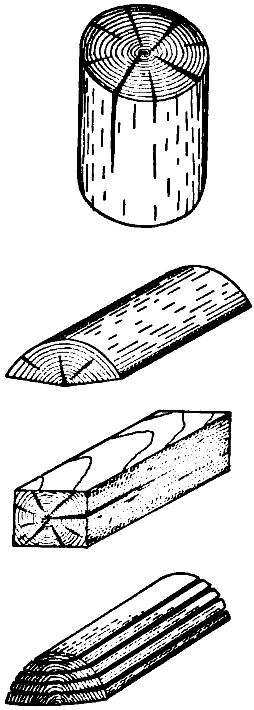
FIG. 11. — Effects of Shrinkage. (Bull. 10, U. S. For. Div.)

Another class of checks, more important than the temporary checks, because they are likely to be larger and are permanent, are those caused principally by the greater shrinkage of timber in a tangential direction along the rings than that along the radius. The occurrence of the rays in radial planes often contributes to the formation of these large radial checks, because they form a plane of weakness at the very point where the strains are the greatest and most complex (two severe stresses existing at right angles to each other, owing to the shrinkage of the rays opposing the shrinkage of the main wood fibres). The danger of the occurrence of large checks of this nature constitutes a serious difficulty in seasoning large timbers, and especially round timbers such as poles, piles, and posts. Too rapid seasoning always increases the danger of injury by excessive checking.

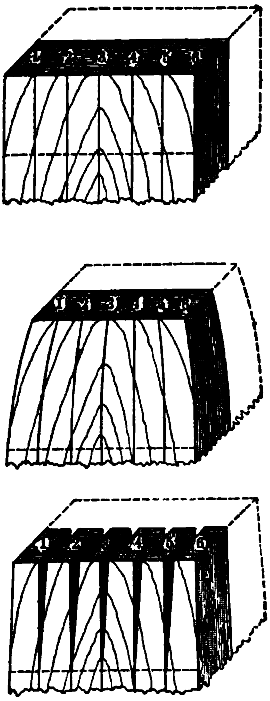
FIG. 12. — Formation of Checks. (Bull. 10, U. S. For. Div.)

Some woods, mostly hard woods, become "case-hardened" when rapidly dried in the kiln; that is, the outer part dries and shrinks, and commonly checks, while the interior is still practically in its original condition. The drying of the interior is thus retarded, but when it does occur great internal strains are set up, resulting in the formation of large or numerous radial checks which follow the rays. When these checks are comparatively small, but numerous, the wood is said to be "honeycombed." The case-hardening of timber may be avoided by air seasoning before placing it in the kiln or by admitting steam to the kiln.

Wood, when dried, has the ability to reabsorb water from the atmosphere. This property is termed "hygroscopicity." The amount of hygroscopic water thus acquired always exceeds the moisture content of the air, but varies with the humidity. The consequent shrinking and swelling of the wood is a serious hindrance to its use where exact fitting is desired. The hygroscopicity of wood may be reduced, but not eliminated, by prolonged exposure to temperatures in the neighborhood of 100° C. (212° F.), or by boiling, steaming, or prolonged soaking.

The harmful effect of the shrinking or swelling of wood used in interior finishing may be minimized on the one hand by avoiding large continuous surfaces by paneling, etc., or, on the other hand, by rendering the wood more or less impervious to moisture by the use of coatings of oils, paints, varnishes, etc.

MECHANICAL PROPERTIES OF WOODS

16. General. The intelligent use of wood for any structural purpose requires a general knowledge of the mechanical properties of different woods, in order that the one selected may conform in its structural qualities to the requirements imposed, and in order that a given purpose may be served at a minimum expense.

Wood is not like many other structural materials in that its mechanical properties are extremely variable, not only between different species and different trees of the same species, but also between specimens cut from different portions of the same tree. An assumption as to the mechanical properties of certain timber of a given variety can therefore be predicated upon the results obtained in tests of timber of that variety only in a most general way, unless detailed information concerning the many factors governing the mechanical properties of both test timber and commercial timber are known. Some of these important factors are: (1) correct identification of species and variety, and knowledge of locality of growth, (2) age, rate of growth of trees and density of the wood, (3) position of test specimens in the tree, (4) moisture content, and

(5) relative freedom of test specimens and commercial timber from defects such as knots, checks, etc. Even if all this information is available the conclusion reached concerning the probable strength is only approximate, because the exact weight of each of the above factors has not been definitely established. We have, however, fairly definite information concerning the allowance to be made for variation in the moisture content and rate of growth.

17. Tensile Strength. The tensile strength of timber is not an important property except in so far as the tensile strength is involved in all cases of transverse loading. Timber used in construction is practically never subjected to pure tensile stresses for the simple reason that the end connections cannot be so devised that they do not involve either shear along the grain or compression across the grain, and, since the resistance offered by any timber to compression across the grain, or shearing stress along the grain, never amounts to more than a small fractional part of the tensile strength, it is evident that considerations of economy in the design of structures will usually call for the use of iron or steel instead of timber for those members which must withstand tension.

Failure in tension across the grain involves principally the resistance offered by the thinner-walled wood elements to being torn apart longitudinally. Wood sustains in tension across the grain only a small fraction (one-tenth to one-twentieth, perhaps) of the load carried in tension along the grain.

Failure in tension along the grain involves principally the resistance offered by the wood elements to being torn apart transversely or obliquely. The strands of wood elements are practically never pulled apart by failure of the union between adjacent strands or fibres. Cross grain from any cause whatsoever is prejudicial to tensile strength. Knots similarly weaken wood subjected to longitudinal tension because of the likelihood of their being either loosely connected with the adjoining wood substance, badly checked, or structurally impaired by a pith cavity.

The only importance of tensile strength in the direction of the grain arises from the circumstance that the lower side of a beam subjected to transverse load is obliged to withstand tensile stresses. This case will later be discussed under the head of cross-breaking strength and stiffness.

18. Compressive Strength. The compressive strength of wood in a direction normal to the grain is simply a matter of the resistance offered by the wood elements to being crushed or flattened. The cells with the thinnest walls collapse first and the action proceeds gradually. A load which cannot be exceeded will generally be reached (the specimen continuing to distort without increase of load), but there is no such thing as a breaking load in transverse compression of wood.

The endwise compressive strength of wood, i.e., the strength of wood in compression along the grain, is dependent upon the anatomical structure and the moisture content of the wood, and the manner of failure is fixed by these same factors. The individual fibres (or other elements) of wood act as so many hollow columns bound firmly together, and failure involves either buckling or bending of the individual fibres or bundles of elements. Buckling is characteristic of any thin-walled cells when dry, as in the case of the early wood of many species, the vessels of others, and the wood of seasoned white pine, spruce, etc., as a whole. Bending is typical of all green or wet woods, and of those portions of any wood which are made up principally of thick-walled cells, whether wet or dry. The isolation of bundles of elements is very frequently caused by longitudinal splitting, which occurs by a tearing of the fibres of the wood, including those of the rays.

The presence of moisture in wood decreases the stiffness of the cell walls, and lowers the compressive strength very materially in consequence. Moisture also facilitates the separation of the fibres from one another.

From the above considerations it will be apparent that the principal factors affecting the compressive strength along the grain are: (1) the actual amount of wood substance encountered in a section, i.e., the density of the wood, (2) the strength of the union between the wood fibres or longitudinal strands of wood elements (particularly as affected by contained moisture), (3) the stiffness of the wood fibres or longitudinal strands of elements (again largely a matter of moisture content), and (4) the continuity of the course of the longitudinal strands in a direction parallel to the axis of the piece. Woods in which the separate elements are closely interlaced and bound together, without the existence of distinct longitudinal planes of weakness, such as exist in ring-porous woods, for instance, will be stronger than woods of opposite character; well-seasoned woods will be stronger than green woods, the stiffness of which is decreased by a high moisture content; and straight-grained woods will be stronger than cross-grained or knotty woods, or woods in which rays are large and abundant.

Thus we find that the strongest of our common woods in compression with the grain are the dense and tough hickories, birches, hard maple, locust, etc.; oaks, long-leaf pine, elm, ash, etc., rank next; short-leaf pines, western hemlock, beech, cedar, cypress, etc., are placed in a third division; while basswood, butternut, chestnut, hemlock, spruce, soft pines, fir, etc., are ranked among our weakest woods. Tabulations of the mechanical properties of some of the principal lumber woods of the United States will be found at the end of this chapter.

19. Cross-breaking Strength and Stiffness. The cross-breaking strength of any material is necessarily closely related to the tensile and compressive strength of that material, since the stresses encountered in a specimen loaded transversely are principally tensile stresses in the lower portion of a beam and compressive stresses in the upper portion. There also exist certain shearing stresses, consequent upon flexure, which are relatively so small that they may be neglected in considering materials whose shearing strength is a large fraction of the compressive strength. With timber, however, the strength in shearing along the grain is so very small that these stresses cannot be wholly neglected, and it is often observed in tests of timber that the initial failure is by longitudinal shear.

The tensile strength of all timber is greatly in excess of its compressive strength (about three times as much on the average), and the latter will usually be the determining factor in limiting the cross-breaking strength. (Compressive strength will always be the determining factor, assuming there exist no defects such as knots, uneven grain, etc., on the under side of the beam, and that the loading is not so placed as to cause high shearing stresses.) It is apparent, therefore, that the considerations which fix the compressive strength similarly affect the cross-breaking strength. The computed value of the fibre stress under the breaking load will always exceed the compressive strength. The extreme fibre stress at rupture, i.e., the modulus of rupture, is computed by the rule $f = My/I$, which involves the assumption that the material behaves elastically up to actual failure.

Although the compressive strength is usually the determining factor which limits the transverse strength of wood, it is often only the initial failure which occurs in compression.

The stiffness of timber used structurally as beams is often quite as important as its cross-breaking strength. In plastered ceilings, for instance, the maximum deflection permitted is usually limited to 1/360 of the span, so that timber beams must be so designed as to not only carry the load imposed safely, but also to do so without excessive deflection.

Stiffness of timber is largely dependent upon the same factors as strength. Dense woods are always stiffer than open, porous woods, and heavy woods are stiffer than light woods except in so far as the weight is attributable to moisture contained. Thus the wood of the long-leaf pine is stiffer than that of the white pine, and the wood of the hickory is stiffer than that of the chestnut. All woods are stiffer when well seasoned than when green, and a given timber of a variety showing distinct bands of summer wood will be stiffer if so placed that the general direction of the annual rings in its cross-section is vertical rather than horizontal.

20. Moisture and Strength. All woods gain both in strength and in stiffness when thoroughly air seasoned or kiln dried. The actual net gain which, from a comparison of strength and stiffness of small specimens in the green and oven-dry condition, would appear to be attainable, cannot be even approximately realized in practice, however, because of the operation of several factors which greatly modify the effect of lessened moisture. Checking, for instance, always occurs to some extent in drying lumber and will partially or entirely counterbalance the gain due to drying, the extent of this effect being dependent upon the size and the variety of the timber.

Large timbers dried only by air-seasoning, even though the process is prolonged for several months or even years, seldom lose sufficient moisture to benefit their strength to more than a slight degree. Such timbers, therefore, cannot be safely depended upon to show any greater strength than if they were in the original green condition. The explanation of this fact is that a great part of the moisture which is first evaporated from wood is water which exists only as "free water" in the lumina of vessels and cells, whereas only variation in the moisture content of the walls of the wood elements affects strength in any way. "The degree of moisture at which maximum absorption by the cell walls is reached is called the 'fibre-saturation point' of the wood. After this point is reached added moisture does not lessen the strength of wood. At this point also, wood ceases to swell."

The fibre-saturation point is determined experimentally by tests of the strength of very small specimens covering a large range of moisture content. When further moisture no longer lessens the strength the fibre-saturation point is reached. Tiemann found this point for various woods to be within the following limits: *

	Per cent.
Long-leaf pine	24–26
Red spruce	29–35
Chestnut	24–28
Loblolly pine	23–26
White ash	19–23
Red gum	25
Douglas fir	23
Norway pine	26–34
Tamarack	27–33

Experimental determinations of the strength and stiffness of wood as influenced by moisture have been made in the laboratories of the U. S. Forest Service and are reported in Bulletin 70 and Circular 108. While

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* U. S. Forest Service, Circular 108.

these investigations have not covered all of our important timber woods, much important information has been derived from them.

From the facts observed in this series of tests the following conclusions may be drawn:

Compressive Strength Parallel to the Grain.

(*a*) Loss of moisture does not affect strength, Fig. 13, or stiffness, Fig. 14, in any way until the total moisture content has been reduced below the critical percentage which represents the fibre-saturation point.

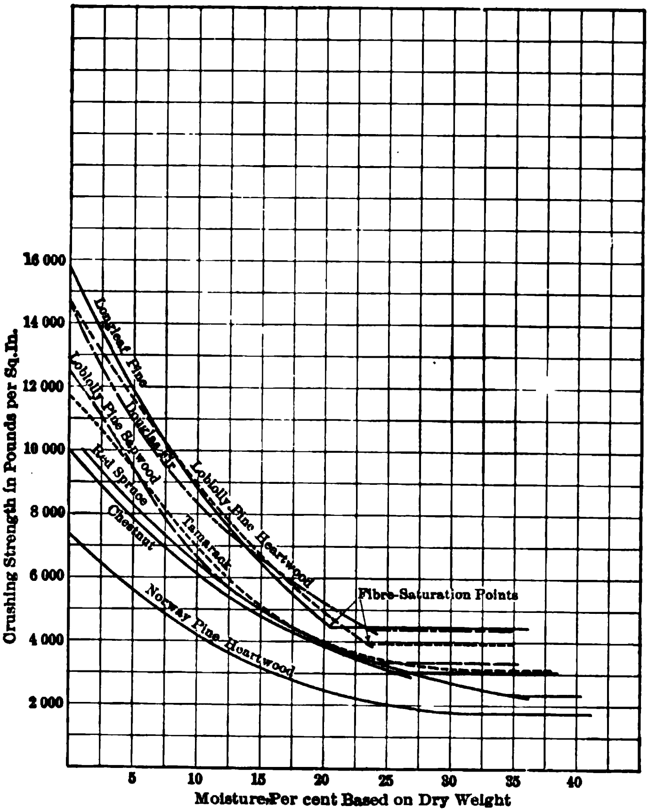

FIG. 13. — Relation between Strength in Compression Parallel to the Grain and Moisture Content for Several Woods. (Cir. 108, U. S. For. Ser.)

(*b*) The fibre-saturation point having been passed, the rate of gain in strength and stiffness varies considerably for different woods, always becoming greater as the total moisture decreases.

(*c*) The green strength of the woods tested amounted, as a rule, to from 50 to 60 per cent of the strength in the normal air-dry condition (12 per cent moisture); and the strength of the kiln-dry woods (3.5 per cent moisture) exceeded the strength of the air-dry woods by from 50 to 70 per cent.

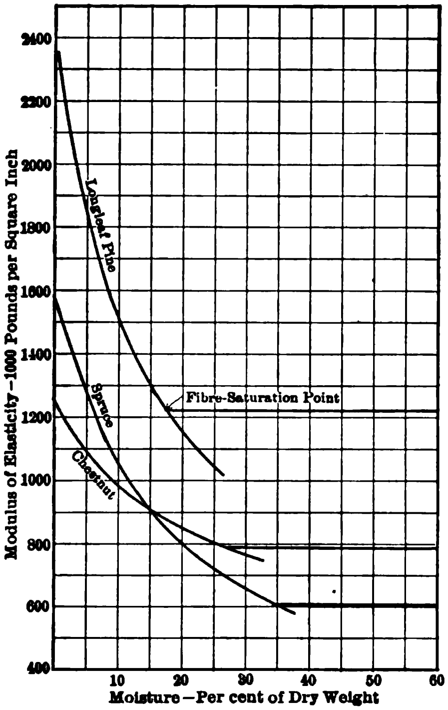

FIG. 14. — Variation of Stiffness in Compression Parallel to the Grain with Moisture Content. (Cir. 108, U. S. For. Ser.)

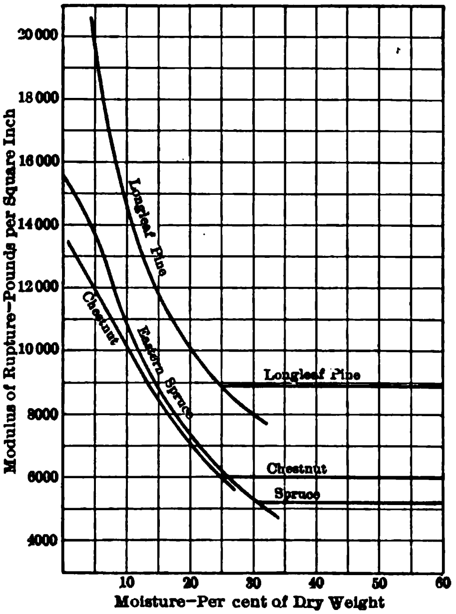

FIG. 15. — Variation of Strength in Bending with Moisture Content. (Bull. 70, U. S. For. Ser.)

Strength in Bending. Modulus of Rupture.

(*a*) Same as (*a*) above, Fig. 15.

(*b*) Same as (*b*) above.

(*c*) The modulus of rupture of green woods of the varieties tested amounted to from 50 to 70 per cent of the value found for the same woods when air-dry, and the modulus of rupture of kiln-dry woods exceeded the value found for the same woods when air-dry by from 33 to 65 per cent.

Stiffness in Bending. Modulus of Elasticity.

(*a*) Same as (*a*) above, Fig. 15.

(*b*) Same as (*b*) above. Effect of moisture is not nearly so marked in case of stiffness as in case of either compressive or bending strength.

(*c*) The modulus of elasticity of green woods of the varieties tested amounted to from 80 to 84 per cent of the value found for the same woods when air-dry, and the modulus of elasticity of kiln-dry woods exceeded the value found for the same woods when air-dry by from 14 to 34 per cent.

21. Weight and Strength. The relation between strength and true density (dry) has been carefully studied at the Forest Products Laboratory, and after analyzing the results of many thousand tests the following expressions have been deduced.

Dry timber. Mod. Rupture $= 26{,}200 \times (\text{Sp. Gr.})^{1.20}$

Green timber. Mod. Rupture $= 18{,}500 \times (\text{Sp. Gr.})^{1.20}$

This is in general true regardless of species. Like all empirical formulas the above are somewhat inexact. The actual data show that mean values for different species and variation in locality may deviate from the calculated value by 30 per cent. This however is no greater variation than may be expected from individual specimens taken at random from any lot of commercial timber. Moreover the above noted formulas have been derived from tests on small, clear, straight-grained specimens.

Hence it is probable that the values given by the "Green timber" formula will be more in accord with the actual strengths of commercial sticks even though such timber be actually partially seasoned.

22. Rate of Growth, Proportion of Summer Wood, and Strength. The average rate of growth of timber is readily computed by counting the annual rings along a radial line and dividing by the length of the line. The indications are that for most species there is a rate of growth which, in a very general way, is associated with the greatest strength. For the species tested this appears to be as follows:

	Rings per inch.
Douglas fir	24
Short-leaf pine	12
Loblolly pine	6
Western hemlock	18
Tamarack	20
Norway pine	18
Redwood	30

23. The Time Factor in Tests of Timber. Timber differs from most other materials in that small variations in the rate of application of load have a more pronounced effect upon the strength and stiffness shown by a specimen under test. If a timber-compression block or beam is loaded rapidly, it will appear to have a higher ultimate strength, and will also appear to be stiffer, than it will if it is loaded less rapidly. This behavior is due to the fact that the deformation lags far behind the load, and if any load is permitted to remain upon a specimen for a sensible time interval the deformation increases, the amount of increase becoming greater for heavier loads. Actual failure appears to be consequent upon the attainment of a certain limiting amount of deformation or strain, rather than a limiting load or stress.

When constant loads amounting to a large fraction of the ultimate strength of timber are sustained for very long periods, the deformation may continue to increase until rupture occurs, even though the stress encountered is far below the ultimate strength of the timber as originally determined. A number of series of long-time tests have shown that for timbers loaded either transversely or in compression with loads amounting to from 50 to 60 per cent of the ultimate strength usually found, failure will ultimately occur, the time required varying from a few weeks to several months.

This important conclusion may therefore be drawn: The strength of timber under any kind of permanent load is only about one-half its strength as found by short-time tests.

24. Tabulation of Mechanical Properties of Structural Timbers. The following tabulation of the mechanical properties of American timber has been compiled from the tests of the U. S. Forest Service.

PHYSICAL PROPERTIES OF A FEW IMPORTANT WOODS GROWN IN THE UNITED STATES

Common and botanical name.	Locality where grown.	Number of rings per inch.	Summer wood (per cent).	Specific gravity (oven dry).	Weight per cubic foot.		Shrinkage from green to oven dry (in per cent of green volume).	Modulus of rupture, pounds per sq. in.		Modulus of elasticity, 1000 pounds per sq. in.		Max. crush. strength parallel to grain, pounds per sq. in.	
					Green.	Air dry.		Green.	Air dry.	Green.	Air dry.	Green.	Air dry.
HARDWOODS.													
Ash, black (*Frazinius nigra*)	Michigan Wisconsin	24	53	0.53	53	*34*	15.2	6,000	*13,900*	1020	*1680*	2,290	*6,890*
Ash, white (second growth), (*Frazinius americana*)	New York	9	63	0.71	51	*44*	14.0	10,800	*18,600*	1640	*1980*	4,610	*9,480*
Birch, yellow (*Betula lutea*)	Pennsylvania Wisconsin	19	26	0.66	58	*44*	16.8	8,600	*18,900*	1540	*2200*	3,460	*9,760*
Chestnut (*Castanea dentata*)	Maryland Tennessee	10	48	0.46	55	*30*	11.6	5,600	*9,700*	930	*1330*	2,470	*6,620*
Elm, white (*Ulmus americana*)	Wisconsin Pennsylvania	18	31	0.54	52	*35*	14.4	6,900	*14,600*	1030	*1490*	2,880	*6,850*
Gum, blue (*Eucalyptus globulus*)	California	.....	.....	0.80	70	*54*	22.5	11,200	*20,600*	2010	*2600*	5,250	*13,900*
Hickory, big shellbark (*Hicoria laciniosa*)	Ohio Mississippi	19	65	0.72	63	*48*	19.2	10,500	*20,500*	1340	*2040*	43,920	*9,710*
Hickory, mockernut (*Hicoria alba*)	West Virginia Mississippi Pennsylvania	18	63	0.74	64	*50*	17.9	11,100	*21,600*	1570	*2380*	4,480	*10,610*
Hickory, pignut (*Hicoria glabra*)	Ohio Mississippi Pennsylvania West Virginia	20	65	0.78	64	*53*	17.9	11,700	*22,500*	1650	*2410*	4,810	*10,640*
Hickory, shagbark (*Hicoria ovata*)	Ohio Mississippi Pennsylvania West Virginia	19	66	0.73	64	*50*	16.7	11,000	*22,600*	1570	*2290*	4,580	*10,700*
Locust, honey (*Gleditsia triacanthos*)	Missouri Indiana	9	45	0.67	61	*48*	10.8	10,200	*16,700*	1290	*1690*	4,420	*9,520*
Maple, Oregon (*Acer macrophyllum*)	Washington	12	.....	0.51	47	*34*	11.6	7,400	*12,000*	1100	*1580*	3,240	*7,180*
Maple, red (*Acer rubrum*)	Pennsylvania Wisconsin	16	24	0.54	51	*37*	12.5	7,800	*14,800*	1420	*1740*	3,350	*7,330*

Maple, sugar (*Acer saccharum*)	Indiana Pennsylvania Wisconsin	21	49	0.66	56	*43*	14.5	9,100	*15,800*	1480	*1820*	3,860	*8,570*
Oak, black (*Quercus californica*)	California Oregon	16	52	0.58	66	*40*	12.1	6,200	*10,500*	740	*1160*	2,800	*8,420*
Oak, red (*Quercus rubra*)	Arkansas Louisiana Indiana Tennessee	11	62	0.65	64	*44*	14.2	7,700	*14,200*	1290	*1870*	3,200	*7,370*
Oak, white (*Quercus alba*)	Arkansas Louisiana Indiana	17	60	0.71	62	*48*	15.8	8,300	*15,200*	1250	*1780*	3,560	*7,610*
Walnut, black (*Juglans nigra*)	Kentucky	12	.....	0.56	58	*37*	11.3	9,500	*17,900*	1420	*1820*	4,300	*10,660*
CONIFERS													
Cedar, Port Orford (*Chamæcyparis lawsoniana*)	Oregon	24	25	0.47	39	*31*	10.7	6,800	*14,500*	1500	*2040*	3,280	*7,750*
Cedar, western red (*Thuja plicata*)	Washington Montana	20	36	0.34	27	*22*	8.1	5,200	*8,800*	950	*1250*	2,840	*6,320*
Cypress, bald (*Taxodium distichum*)	Louisiana Missouri	16	31	0.47	48	*30*	10.7	6,800	*11,300*	1190	*1540*	3,490	*7,690*
Douglas Fir (*Pseudotsuga douglasii*)	Washington Oregon	13	35	0.52	38	*30*	12.6	7,800	*10,300*	1580	*1460*	3,940	*7,090*
Fir, balsam (*Abies balsamea*)	Wisconsin	12	26	0.41	45	*25*	10.8	4,900	*9,900*	960	*1440*	2,400	*6,640*
Fir, white (*Abies concolor*)	California	10	30	0.44	56	*26*	10.2	6,000	*9,800*	1130	*1490*	2,800	*6,150*
Hemlock, black (*Tsuga mertensiana*)	Montana	23	45	0.48	45	*31*	10.8	6,000	*11,400*	940	*1180*	2,890	*7,510*
Hemlock, eastern (*Tsuga canadensis*)	Tennessee Wisconsin	20	34	0.44	48	*28*	10.4	6,700	*9,700*	1120	*1300*	3,270	*7,060*
Pine, Cuban (*Pinus heterophylla*)	Florida	17	44	0.68	53	*45*	12.7	8,800	*18,300*	1630	*2220*	4,470	*11,890*
Pine, loblolly (*Pinus tæda*)	Florida North Carolina South Carolina	8	42	0.59	54	*38*	12.6	7,500	*15,600*	1380	*2130*	3,580	*11,300*
Pine, longleaf (*Pinus palustris*)	Florida Louisiana Mississippi	18	39	0.64	50	*42*	12.3	8,700	*16,700*	1630	*2200*	4,390	*10,880*
Pine, short leaf (*Pinus echinata*)	Arkansas Louisiana	12	40	0.58	50	*38*	12.6	8,000	*13,900*	1450	*1970*	3,810	*8,660*
Pine, sugar (*Pinus lambertiana*)	California	12	34	0.39	50	*26*	8.4	5,300	*8,600*	970	*1210*	2,600	*5,190*
Pine, white (*Pinus monticola*)	Montana	28	33	0.45	39	*29*	11.5	5,700	*11,500*	1330	*1690*	3,070	*7,840*
Spruce, Sitka (*Picea sitchensis*)	Washington	9	24	0.37	33	*26*	11.2	5,500	*11,200*	1180	*1610*	2,600	*5,770*
Spruce, white (*Picea canadensis*)	New Hampshire Wisconsin	14	27	0.43	33	*28*	14.8	5,400	*9,200*	980	*1390*	2,380	*6,020*

Compiled from Bulletin 557, U. S. Dept. of Agriculture.

25. Factor of Safety and Working Stresses. The factor of safety used in the design of timber structures varies considerably. The factors given by different authorities run from 4 to 8 for steady loads and up to 15 for shocks.

As an example of current practice the following table of safe working stresses recommended by the Committee on Wooden Bridges and Trestles of the American Railway Engineering Association is given. These figures apply to green timbers (all large timbers must always be assumed to be no stronger than green timber) of structural sizes used for railway bridges and trestles where always subjected to vibration and shock. The committee recommends that these values be increased 25 per cent for highway bridges, and still more for buildings and similar structures wherein the timbers are protected from the weather and are not subject to impact.

SAFE WORKING STRESSES FOR STRUCTURAL TIMBER

(Adopted by Am. Ry. Eng. Assn., 1909)

(All values expressed in pounds per square inch)

Kind of Timber.	Compression.		Bending, Extreme Fiber Stress.	Shearing along Grain.
	Along Grain.	Across Grain.		
Douglas fir	1200	310	1200	170
Long-leaf pine	1300	260	1300	180
Short-leaf pine	1100	170	1100	170
White pine	1000	150	900	100
Spruce	1100	180	1000	150
Norway pine	800	150	800	130
Tamarack	1000	220	900	170
Western hemlock	1200	220	1100	160
Redwood	900	150	900	80
Bald cypress	1100	170	900	120
Red cedar	900	230	800	
White oak	1300	450	1100	210

DURABILITY, DECAY, AND PRESERVATION OF TIMBER

26. Durability and Decay of Timber.* "The decay of wood is not an inorganic process like rusting of iron or the crumbling of stone, but is due to the activities of low forms of plant life called bacteria and fungi." Bacteria are among the lowest forms of life, often only a single cell which multiplies by division into two cells which in turn divide again. Several such cells united together form a thread or filament of microscopic size.

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* Bulletin 78, U. S. Forest Service.

Fungi consist merely of tiny threads, known as mycelium, which in most of the higher forms grow together to form compact masses as, for instance, the toadstools which grow on rotting logs and the "punks" or "brackets" on the trunks of forest trees. The action of fungi and bacteria in destroying wood is, so far as is known, about the same, and the two will therefore be considered together.

The mycelium starts from a single spore (a primitive substitute for seed, which are born in infinite numbers by the fruiting fungi, and are distributed by the wind). Under favorable conditions the spore sprouts or germinates, sending forth a single thread or hypha which branches and rebranches quickly. The hyphæ creep through the tissues of the material in which they are growing and absorb the materials necessary for their growth. In living cells they attack the protoplastic contents — the starches, sugars, and oils. In dead cells they attack the cell walls. After a time some hyphæ form the fruiting body which bears a crop of spores. The action of the fungi results in complete or partial solution of the substance attacked.

Susceptibility to decay and comparative resistance to decay vary with different classes of timber. The determining factors are as yet almost unknown. Hardness, density, specific gravity, and strength seem to have no influence one way or the other. Some very hard tropical timbers decay very rapidly while others last very long. Hard strong oak decays much faster than light porous cypress; tamarack and hemlock decay rapidly, while cypress and cedar are lasting; elm and birch are short lived, the locust long lived, etc.

27. The Preservation of Timber. The simplest way to prolong the life of timber exposed to the attack of fungi is to reduce the moisture content by seasoning. By piling timber so as to permit free access to air all around it, the moisture may be reduced to about 15 to 18 per cent. Of course the climate and the size of the timbers have a great influence upon the rate of seasoning and the total amount of moisture lost.

The moisture content of air-dry wood may be still further reduced by kiln drying, but the effectiveness of all methods of moisture reduction as a preservative measure must be limited by the fact that timber so dried readily reabsorbs moisture upon being again exposed to dampness, or even ordinary atmospheric conditions and benefits obtained are only moderate.

"By far the best method of checking the growth of fungi, however, is by poisoning their food supply — by injecting poisonous substances into the timber, so changing the organic matter into powerful fungicides." It is a widespread idea that the germs of decay are inherent in the wood, needing only an opportunity for development to bring about its destruction. On the contrary, all wood-destroying agencies start from the outside and may even be excluded by certain paints which merely coat the surface of the timber but which are poisonous enough to prevent the germination of spores.

The first deliberate attempts to preserve timber from decay date back many centuries, when wood was charred to make it more resistant. Later came the period when wood was coated with preservative paints, then came attempts to inject preservatives into the wood.

Of the many antiseptics which have been proposed for the preservation of timber only four have been largely used with success in the United States. These are *creosotes* (dead oil of coal tar), *zinc chloride, corrosive sublimate* (bichloride of mercury), and *copper sulphate.* At the present time copper sulphate and corrosive sublimate are used to only a sligher extent. There are many patented preservatives known by various names, practically all of which have either creosote or zinc chloride as their base.

Creosote is a by-product of coal tar produced at illuminating gas plants and by-product coke oven plants. *Wood creosote,* distilled like coal tar from wood, also possesses strong antiseptic properties. *Zinc chloride* is obtained by dissolving metallic zinc in hydrochloric acid. This is diluted with water before being used as a wood preservative. Creosote has the advantage of insolubility in water, so that it will not wash out of timber; zinc chloride is often preferred for use in comparatively dry situations.

The processes by which preservatives are injected into timber may be divided into two general classes, the "pressure processes" and the "non-pressure processes," the distinction being only in the fact that in the former force pumps, air compressors, etc., are utilized, while in the latter only atmospheric pressure is relied on.

The Pressure Processes

The Breant Process. One of the earliest practical pressure processes was that devised by Breant in France in 1831. The timber is inserted in a vertical cylinder and the liquid forced in almost to the top. A vacuum is produced by opening a connecting valve to an auxiliary chamber which has been exhausted by an air pump, after which the valve is closed and the liquid forced in till a pressure of 10 atmospheres is reached. The time required for impregnation is about six hours.

The Bethall process, a modification of the Breant process, using creosote, and the process of *Burnettizing,* using zinc chloride, are the most widely used pressure processes. The method of injection is practically the same for each. The timber to be treated is placed on iron trucks or "cylinder buggies" and run into huge horizontal cylinders 8 or 9 feet in diameter and often as much as 150 feet long, after which the doors are hermetically sealed. Live steam is admitted at a pressure of 20 pounds per square inch for several hours, then the steam is blown out, the vacuum pump started, and within a few hours as much air and moisture as possible are exhausted. Finally, the preservative is run into the cylinder at a temperature of about 160° F. (71° C.), the pressure pumps are started, and the desired amount of preservative is forced into the timber. The surplus preservative is now blown back into the tank, the timber allowed to drip for a few moments, and then withdrawn.

The boiling process is used principally for Douglas fir on the Pacific coast. The timber is placed in the cylinder, which is filled with creosote slightly above the boiling-point of water, and kept in this condition for a period of from a few hours to two days, during which time water and volatile oils are driven off. Finally a pressure of 100 to 125 pounds per square inch is applied and the temperature is allowed to drop, thus forcing the preservative into the timber.

In the *A. C. W. process* the procedure is like that of the Bethall except that air pressure (15 pounds per square inch) is applied after the vacuum, and maintained while the creosote is admitted in order to prevent unequal absorption during the filling of the cylinder. Then 100 pounds per square inch pressure is applied till the penetration reaches the desired degree, after which the preservative is drawn off and air forced in at a pressure of 60 to 80 pounds per square inch to increase the penetration of the preservative.

The Rüping process is largely used with creosote, and is the best known *empty-cell* process. The timber is air-dried before being placed in a cylinder. Air is forced in at 75 pounds per square inch pressure till the wood is filled with the compressed air. Then, without abating the pressure, the oil is admitted at a higher pressure (80 to 85 pounds per square inch). The pressure is subsequently increased to 225 pounds per square inch. This forces the penetration of the oil into the timber. Finally the valves are opened, the excess oil is drawn off, so relieving the pressure around the timber, and the expansive force of the compressed air in the wood forces out much of the oil, leaving only a coating around the cell walls, thus resulting in a deep penetration with a light absorption.

The Lowry process tries to accomplish the same effect without using compressed air. The air-seasoned timber is introduced into the cylinder, oil is admitted, and a great pressure applied, causing a compression of the air in the wood cells and intercellular space. Finally the oil is withdrawn, a strong vacuum is formed and the expanding of the compressed air forces out the oil as in the Rüping process.

The creo-resinate process consists in impregnating the timber with a mixture of creosote and resin (50 to 75 per cent creosote). The method differs from the Bethall process only in using dry heat instead of a steam bath before the vacuum.

The Wellhouse process is an attempt to prevent the leaching out of zinc chloride from treated timber. It relies for its efficiency upon the tendency of glue and tannin, when combined, to form a leathery, waterproof substance, or "leatheroid." A ½ per cent solution of glue is mixed with the zinc chloride solution and forced into the timber, and a tannin solution is afterward forced in. The formation of "leatheroid" in the cell openings tends to prevent the absorption of water and the leaching out of the salt.

The Allardyce process is an attempt to devise a process cheaper than one using creosote and not involving the leaching out of zinc chloride. Zinc chloride in a 2 or 3 per cent solution is first forced into the timber (12 pounds per cubic foot) by a process similar to "Burnettizing" and then creosote is injected (3 pounds per cubic foot of timber). The creosote remains largely on the exterior and is designed to protect the soluble chloride in the interior.

The card process is a similar one in its objects. The preserving fluid contains 15 to 20 per cent of creosote, and a 3 to 5 per cent solution of zinc chloride for the remainder. After a steam bath and vacuum the preservative is admitted under pressure. The two preservatives will not mix, and are of different specific gravity, so they are kept in a mechanical mixture by a centrifugal force pump which draws the solution from the top and forces it back through perforated pipes running along the bottom of the cylinder.

The Non-pressure Processes

Injection of preservatives by the non-pressure processes depends on different principles from those involved in the pressure processes. The wood, after being seasoned in air, is immersed in a bath of hot liquid in a suitable containing vessel for from one to six hours, during which time the air and moisture in the wood expand and partially pass off. Then, as quickly as possible, the wood is changed to a bath of cooler preservative. This causes contraction of the imprisoned air and moisture, creating a partial vacuum which is subsequently destroyed by the entrance of the preservative. *Green-timber processes* prolong the hot bath until much of the moisture in the green wood has been expelled. Air is not present to help in forming a vacuum, so the treatment is slow and unsatisfactory, as well as expensive, through loss of time and evaporation of the preservatives.

The oven process is founded upon the fact that the hot bath serves only to expand the air and moisture, and drive them out, with practically no penetration of the preservatives until the cold bath is reached. Much the same results may sometimes be secured by subjecting the timber to dry heat in an oven or kiln and then immersing quickly in a bath of cold preservative. Only in special cases is the process desirable, as when a metal-corroding preservative is used and metal tanks and steam coils cannot be employed, in which case the dry hot timber is plunged into a cold bath in a wooden tank.

The Empty Cell Non-pressure Process

In the non-pressure processes empty cells cannot be secured by vacuum, force pumps, etc., so that the problem of securing a good penetration with a small quantity of preservative used presents itself. But here again the non-pressure processes have proven successful, and for some of the more porous woods the depth of penetration and the economy of preservative compares favorably with empty-cell processes in pressure treatments.

Practically the only difference in this process from the usual non-pressure process is that here the length of time of immersion in the cold bath is shortened. Suppose that the hot bath has partially expelled the air and moisture to a depth of 3 inches in a timber. When the cold bath is applied the drop in temperature first takes place in the outer band of wood, causing the partial vacuum to first form there. This causes an inrush of the preservative which fills the intercellular and cellular space. If the timber is withdrawn before the preservative has penetrated more than 2 inches, instead of the 3 inches affected by the hot bath, the subsequent cooling of the third inch causes a further vacuum to form, and subsequently be destroyed by the admission of superfluous oil from the outer saturated portion, thus resulting in a depth of penetration of 3 inches with the amount of preservative required to saturate 2 inches. A second hot bath is sometimes employed with similar results. The oil is a better heat conductor than the wood, causing a further heating of the interior, resulting in second expansion and expulsion of air and moisture, with the formation of a partial vacuum which is destroyed by the increased penetration of the excess oil in the outer portion when the stick is exposed in air.

The low-pressure process, developed by the Forest Service, consists in subjecting the seasoned timber first to a hot bath to cause expansion and expulsion of air and moisture followed by a cold bath. In this latter bath atmospheric pressure is not depended upon, but low pressure, not exceeding 70 pounds per square inch, is applied by means of the pumps which force in the preservative. The treatment is carried out in cylinders as in ordinary pressure processes.

The non-pressure processes and the low-pressure processes can be used only in a restricted field. They are not adapted to use with non-porous woods or where large quantities of timber must be treated in a short time.

Superficial Treatments

Less efficient but cheaper treatment can be secured by painting the face of the timber with at least two coats of hot creosote or some similar preservative (the *brush method*). The liquid will not penetrate to any great extent, but as long as there remains an unbroken antiseptic zone around the surface the spores of the fungi cannot enter. Thorough air-seasoning before painting is necessary, since otherwise checks may form and provide a means of access to the interior of the timber for the spores of the fungi.

A still less expensive treatment than the brush treatment is the method of dipping the timber in an open vat of the preservative. Usually the timbers are carried through the bath on chain conveyors and remain submerged only a few minutes at most. *Dipping* is not only more economical of time and labor, but gives better results than the brush method.

Effect of Preservative Treatments upon Strength of Timber

The effect of preservative treatments of timber upon strength has been investigated by the Forest Service under the charge of Professor W. K. Hatt.* It appears in general that the strength of treated timber depends, first, on the percentage of moisture remaining in the wood, and second, on whether the wood has been subjected to injuriously high temperatures during the process of steaming and the vacuum treatment. A high degree of steaming is injurious to wood, the limit of safety depending upon the quality of the wood, the degree of seasoning, and the temperature and duration of the steam bath. For loblolly pine this limit was found to be 30 pounds per square inch for four hours or 20 pounds per square inch for six hours. During steaming the amount of moisture in the wood must be increased with consequent weakening of the fibres if the vacuum following the steam is not able to remove the added moisture. There seems to be no ground for believing that non-pressure processes can be injurious to the strength of the timber.

The presence of creosote in itself will not weaken wood, since it appears not to enter the cell walls and fibres, but only to coat them, and so,

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* Circular 39, U. S. Forest Service.

if the wood is not perfectly seasoned, the temperature of the bath may aid the seasoning and increase the strength of the wood.

The presence of zinc chloride will not weaken wood except by the addition of water by reason of the fact that it is in itself a water solution. Subsequent seasoning will obviate this difficulty. A too-concentrated solution may cause chemical dissolution of some of the wood fibres, but this danger can easily be avoided

SECTION 8

CHAPTER I

FIBRE ROPE

1. General. From the most ancient times ropes have been made by twisting together all sorts of materials, such as roots, grasses, strips of bark, skin, hair, rawhide, leather, vegetable fibres, etc. At present the term rope or cordage is applied to the product obtained from a comparatively small number of vegetable fibres. The fibres most commonly used are, *Manila, sisal, Java, New Zealand, hemps* from various countries, *jute* and *cotton.*

2. Classes of Fibres. Fibres may be divided into two classes, *hard fibres* and *soft fibres.* Manila and sisal belong in the first class and the most important soft fibres are hemp, flax and jute.

The hard fibres grow in the substance of the leaves and bark and are surrounded by a pulpy matter. The soft fibres all grow in a thin layer just under the bark of the plant. The soft fibres are also known as *bast* fibres.

There are some fibres used for rope making that do not properly belong to either of these classes, such as New Zealand and cotton. Cotton is not used for rope making except for very special reasons.

3. Extraction of the Fibres. The hard fibres are extracted by scraping away the pulpy matter of the plant from the layers of fibre. This can be accomplished by machinery in the case of sisal but manila fibre must be cleaned by drawing under a knife hinged over a block of wood, the work being done by hand. The quality of the fibre depends very largely upon the care with which the cleaning process is carried out.

The soft fibres are treated in a very different manner. The stalks are cut and immersed in water to soften and rot away the gummy substance that holds the fibres together. This operation is known as "retting." The stalks are then removed from the water and dried. The fibres are cleaned by "breaking" and "hackling." The dry bark is first broken into small pieces that fall away and the fibres are then drawn through a comb that removes the last traces of bark and dirt.

FIBRES USED IN ROPE MAKING

4. Manila, Sometimes Known as Manila Hemp or Abacá. Manila fibre is obtained by scraping the pulpy matter of the wild banana plant (*Musa Textilis*) of the Philippine Islands, away from the fibres. Its characteristics of length, strength, texture and color are affected by climatic conditions, the care taken in cleaning and the portion of the plant from which the fibre is taken. There are a number of different grades of manila. The fibre varies considerably in color and is from four to sixteen feet in length. The properties that make this fibre desirable for rope are its strength, durability and ease in handling. Manila fibre is very smooth and pliable.

5. Sisal. Sisal is grown in Mexico and is obtained from the leaves of a plant of the Agave family (a kind of cactus), the barky material being scraped away from the fibre. The length of the fibre runs from two to four feet. The color of the fibre is a yellowish white. Compared with manila Mexican sisal is a harsher, coarser fibre, approximately two-thirds as strong and does not have as good handling qualities. Unpleasant splinters will be usually encountered in a sisal rope or a manila rope adulterated with sisal.

Its principal use is in twine and tying materials which are used at most only a few times. It is not as durable as manila and will rot under exposure to weather comparatively quickly. It is often used to adulterate the cheaper grades of so-called manila rope.

6. Java. Java fibre is somewhat similar to sisal, but generally speaking is of a better quality in that it is softer, has better color and greater strength. It is approximately seven-eighths as strong as manila. It is used largely in binder twine and has certain applications in rope. It suffers from the same trouble as sisal on exposure to weather.

7. New Zealand. (A species of flax.) New Zealand is rather soft and runs from five to eight feet in length. It is approximately four-fifths as strong as manila. Its use for rope is rather restricted. In general appearance it more nearly resembles manila than any other fibre.

8. Hemps. There are various varieties of pure hemp all of which are obtained from the same plant grown in different localities. The principal kinds are — American hemp, Italian hemp, Russian hemp and Java hemp. Hemps are used for the smaller tarred ropes and twines for the reason that their strengths are high and the nature of the fibre such that considerable tar can be taken up and retained. While the hemp obtained from different countries varies considerably in strength, it may be said that the true hemps are slightly stronger than manila. Hemps are bast fibres, being obtained from the bark of the plant. The fibre is obtained from the stock of the hemp plant, which is first cut, then retted, either on the ground by dew or frost, or by immersion in water, which action dissolves the gummy constituents in the stock, allowing the barky or woody portion to be broken and combed out.

9. Jute. This fibre is obtained from the inner bark of a tall, Asiatic herb of the linden family. This fibre is coarse and rough and is used for the cheapest qualities of tie stuffs.

10. Cotton. A good grade of cotton fibre is used for rope. A fairly strong and rather soft rope is produced. This rope is not durable and is not used for many engineering purposes. Cotton twine is a very common commodity.

ROPE MANUFACTURE

11. Lubrication. Practically all fibre to be made into rope is first treated with some sort of lubricating compound, whose principal constituent is usually a petroleum oil. The purposes of this lubricant are to make the fibre work easier in the processes of manufacture and to increase the durability of the product. There are, however, certain products of the cordage factory on which no lubricant can be used. Examples of this class of product are the small cords and tie stuffs used for bundling fine leathers or other fabrics where oil would be liable to stain the goods.

12. Process. The process of rope manufacture is similar to that used for most textiles, consisting of combings, doublings and drawings, the purpose of which is to produce an even and uniform sliver which may be spun into the rope yarns. The yarns are then twisted together into strands and the strands are twisted together into rope. The degrees of twist which are used and the final result are spoken of as "the lay" of the rope. In plain laid or ordinary rope, there are three twists, first the twist in the yarn, second the twist in the strand, which is opposite to the twist in the yarn, and finally, the twist in the rope, which is opposite to the twist in the strand and therefore in the same direction as the twist in the yarn. The twist in the strand is spoken of as the "fore-turn" of the rope and the twist in the rope is spoken of as the "after-turn."

Products that fall under the general heading of tie stuffs, such as hay rope, bale rope, lath yarn, twine, etc., consist either of one thread alone or of a comparatively few twisted together. Such products do not properly come under the heading of rope.

13. Construction. Ropes are made three-strand, four-strand or six-strand, the last two usually with hearts or cores.

The three-strand rope is the general construction and is used except where the four- or six-strand rope has some particular application. A four-strand rope presents a greater surface and therefore is used where wear is a factor. It is also more flexible. The purpose of the heart or core is to hold the four strands in their proper relative positions when the rope is subjected to external pressure as in the case of hoisting or transmission rope. Four-strand ropes without heart are not common, except in the very smallest sizes. A four-strand rope has approximately the same strength as a three-strand rope of the same size.

A six-strand rope is a very special construction and is used only where flexibility and wearing surface are the governing factors.

14. Lays. There are two common types of lay, either the plain lay, where the whole rope is composed of three strands, or the cable lay, where the whole rope is composed of three or sometimes four smaller ropes laid together, the twist being in the opposite direction to the twists in the small rope. The plain lay is the common construction. The cable lay is used where more spring and elasticity are required than would be obtained with the plain lay. Cable lay is used in wrecking cables and drilling cables. The surface of a cable laid rope will present a greater resistance to wear than will the softer surface of a plain laid rope.

When a weight is suspended on a rope, the rope will untwist and become longer. In untwisting the rope the strands are untwisted and the yarns are twisted more tightly in the strands. The end of the rope will revolve until a balance is produced between the stress caused by the untwisting of the strands and the resistance offered by the yarns being more tightly twisted in the strands. The relative amount of twist for strands and yarns has been determined by long experience.

15. Degrees of Lay. Ropes of any number of strands, either of plain laid or cable laid construction, may be twisted to a greater or less extent. Where the twist is considerable, the rope is designated as a hard laid rope and where less, as a soft laid rope. The degree of twist in a rope is dependent upon the use to which it is to be put. Sailmakers' bolt rope may be mentioned as a sample of a soft laid rope. This rope is sewed along the edges of sails and therefore must be soft. Hoisting rope may be mentioned as an example of hard laid rope.

Generally speaking a hard laid rope is weaker and a soft laid rope stronger than the common or medium laid rope. Ranges between the two extremes may be as great as twenty per cent. The cable lay is less strong than the plain lay. The straighter the fibres the stronger the rope. This is explained by the fact that when a rope breaks the fibres do not pull apart but are cut or sheared off by the action of one upon another; therefore the less direct the pull, the greater will be the shearing action. The strength of a yarn is not as great as the aggregate strengths of the fibres which make it up. The strand is not as strong as the aggregate of the yarn strengths which make it up and the rope is not as strong as the aggregate of the strand strength.

16. Methods of Manufacture. Ropes are manufactured by the rope walk method or by the factory method. In the rope walk method the yarns are formed into strands by being drawn through perforated plates, and then through a compacting tube. They are then attached to a moving carriage, fitted with a twisting apparatus. The carriage moves down the rope walk, pulling the yarns off their bobbins, through the compacting tube at the proper tension and twisting them together into a strand (giving the fore-turn). The strands thus formed are attached to a similar machine that closes the rope by giving the after-turn or twist as it moves down the walk.

In the factory method, the two machine method or the one machine method is used. In the two machine process, the strands are formed from the yarns by passing through flyers that put in the fore-turn; the strands are then wound on spools and passed to the second machine which forms the rope from the strands in the same general manner. In the one machine process, a single machine carries out both of these operations, the finished rope passing away to a reel at the top of the machine. Only comparatively small ropes can be made by the single machine process. A fairly large rope can be made by the two machine process. Very large ropes, cables and hawsers are usually made in the rope walk. A much longer rope can be made by the machine process than by the rope walk method.

MANILA ROPE

17. Grades. Manila rope is made in various grades, from corresponding grades of fibre. The greatest proportion of manila rope produced for general purposes is designated simply "manila rope."

Bolt Rope. This grade is made from selected fibre and is of a much higher grade than the regular manila rope. It has a much better color and its wearing qualities are very good. Transmission ropes and tow lines are of this quality.

Yacht Rope. This is the highest grade of manila rope and is manufactured in comparatively small amounts. It is very white in color and the fibre is extremely fine and silky. It is used where appearance and smoothness of the rope are of particular importance, such as running rigging for yachts.

Hardware Grades. There are on the market grades of manila rope which come below the regular manila rope, which are spoken of as hardware manila rope, or second and third grade manila.

Ropes of other fibres than manila are usually made in one grade alone with the exception of hemp ropes, which are made in high and low grades.

ROPES FOR SPECIAL USES

18. Tarring and Special Lubrication. Ropes for certain uses demand special treatment in the process of manufacture. The most common of these is that of tarring, where either the yarn, or, in the case of small ropes, the rope itself, is run through a bath of hot tar, thoroughly impregnating it. The purpose of the tar is usually for protection against moisture. Tarred rope will not swell to any extent in water. Pine tar is generally used.

Hemp ropes and fittings are very frequently tarred to protect them against moisture. Sisal tie stuffs, such as lath yarn, which is used to tie up bundles of lath, are sometimes tarred, to protect the sisal against dampness and also to prevent the knots from slipping.

Certain types of rope require lubrication in addition to that furnished by the normal lubricating of the fibre in the process of manufacture. Power transmission ropes and cables used in well drilling are examples. The purpose of the additional lubrication is to reduce the internal friction of the rope.

19. Internal Wear. When a rope is bent over a sheave, the strands and yarns slide and rub on each other, causing friction and wearing the rope internally. If a worn out rope is opened by untwisting the strands, a fine powder and slivers of fibre will be found, showing that the fibres, by rubbing on each other, have been ground to pieces. This difficulty is overcome by lubricating the inside fibres and cores with plumbage and tallow, or some other suitable lubricant, to prevent this internal chafing and wear.

20. Transmission Ropes. Transmission ropes are made from the selected grades of manila, and are of four-strand construction. The conditions of use require a rope so lubricated as to take care of internal friction, and a construction which will reduce the external wear to a minimum. It is very important that the lay shall be even, so that all the strands will bear evenly, and the lay shall be of such a nature that it may be properly spliced. The stretch of the rope should also be reduced to a minimum.

21. Hoisting Ropes. The requirements for hoisting ropes are much the same as for transmission ropes and it is usual to employ the same grade of manila. The more severe external wear to which these ropes are subject, however, makes it desirable that the lay be harder.

22. Drilling Cables. The cables used in oil well drilling are commonly made from the same grade of fibre employed in regular manila rope. They are cable laid, in order to produce a springy and lively line. They must be well lubricated to take care of the friction. The lay must be even and must be in such a direction that the tendency to untwist will not unscrew the drilling tool.

23. Tie Stuffs. Most tie stuffs are made of sisal, although manila and New Zealand are employed to a certain extent. They are sold under various names, such as binder twine, hay rope, hide rope, paper twine, lath yarn, bale rope, etc. The name indicates the use to which they are to be put. They must be strong enough to stand the work required and have the proper physical characteristics.

24. The Use and Care of Rope. A fibre rope can stand a certain amount of neglect but it must be remembered that the rope is made of vegetable fibre and that a certain amount of care is essential. Conditions of use should be avoided that will subject the rope to abrasion, cutting, too sharp bending, exposure to heat, and especially to exposure to acid or strong alkali. Sharp bending will tend to break the fibres and produce internal strains which are very serious. In power transmission and hoisting ropes the sheaves must be large enough to prevent this condition. Damage by acid is a common cause of rope failure, as it needs only a very little weak acid to ruin the fibre. Fairly strong alkali also ruins a rope and heat damages the fibre seriously.

Fastenings. When a rope is used it must be tied or spliced. A knot is much weaker than the rope but splicing, if properly done, decreases the strength but little. Poor splicing, however, is common.

Efficiency of Knot or Splice. The strength of dry rope considered as 100

	Per cent		Per cent
Long splice	95	Eye splice	90
Short splice	80	Timber hitch or half hitch	65
Bowline	60	Square knot	50

Coiling. Coiling or uncoiling in one direction will either put in or take out some of the turn of the rope, whereas coiling or uncoiling in the other direction will reverse the process. Sometimes enough turn is put into the rope so that it will kink badly and be hard to handle. Rope should be straightened and stretched in a normal condition before being used. In uncoiling transmission rope, the coils should be slung on a rod through its axis, and the coil revolved as the rope is unwound. Or the coil should be rolled on the floor, paying off the rope as it moves.

Hoisting and other ropes should be uncoiled as follows: Loosen the burlap cover at each end of the coil. One end of the rope will be found on the outside of the coil and the other on the inside. Turn the coil down with its axis vertical in such a manner as to bring the end of the rope that is on the inside of the coil at the bottom. Reach down through the coil, grasp the end of the rope and draw it upwards out through the center of the coil. Do not, under any circumstances, uncoil the rope from the outside of the coil.

25. Properties of Rope. The factors to be considered in purchasing rope are: — quality, strength, durability, suitability and weight. Rope and cordage are usually sold by the pound and the weight of a certain length is particularly important. There have been many instances where rope which apparently was cheaper, based on the price quoted per pound, turned out to be much more expensive than a rope which was quoted at a considerably higher price per pound, as the cheaper rope was much heavier and therefore the length per pound less.

Where purchases are made in accordance with specifications, the specifications must be carefully considered. Many rope specifications are of little value, because of the fact that the factors influencing the value of the rope are not properly handled. A satisfactory set of specifications for manila rope were drawn by a committee of rope makers working with a representative of the Bureau of Standards. The following is an outline of their requirements.

1. Material or grades of manila fibre.
2. Maximum weight and minimum strength.
3. Allowable variation in circumference from the nominal size.
4. Minimum and maximum quantities of lubricant.
5. Method of packing and amount of tare.
6. Method of ordering and length of coils.
7. Markings of the packages.

26. Physical Requirements. (For manila rope.)

Maximum Weight. Place on the rope a load P pounds equal to 200 times the square of the diameter in inches ($P = 200\,D^2$). While the specimen is under this load mark off a certain length. This length shall be weighed and the weight per foot obtained, using the length obtained under stress.

Breaking Strength. The specimen shall be held in the machine by means of eye splices, either wet or dry, using a 7-inch eye and at least three tucks in the splices. Run load up to two-thirds of calculated breaking strength at any speed desired, then the specimen shall be broken at a speed between one inch and four inches per minute. The length of specimen between eyes shall be five feet.

Size. Circumference shall be determined by means of a thread or rope fibre when the specimen is under the load of $P = 200\,D^2$. In the case of a three-strand rope, the circumference is three times the diameter. For a four-strand rope, a trifle more.

Formulæ for Breaking Strength. For average three-strand manila $7000\ D^2 + 600$. High grade manila is stronger than this in the smaller sizes. The strength of four-strand transmission rope is usually taken as $7000\ D^2$ pounds and the weight as $0.34\ D^2$ pounds per linear foot. The constant 7200 is sometimes used in the strength formulæ. The allowable tension for a transmission rope is usually taken as about $200\ D^2$ pounds.

Rope sizes are given by both circumference and diameter, the former being preferable and it is always desirable to specify so that there shall be no misunderstanding. For the three-strand rope the circumference, as determined by fibre or thread, is three times the diameter and for a four-strand rope, a little more than three times.

The standard package for most types of rope is 1200 feet or 200 fathoms per coil. Half coils are common but shorter lengths call for an advanced price.

27. Adulteration of Manila Fibre. Work 35 per cent bleaching powder into a thick paste with water, then add about six times the resultant volume of water. Allow to settle over night, then draw off the clear liquid into a dark colored glass bottle. Before using, acidify the part to be used with acetic acid. Separate the strands of the rope to be examined, rinse out the oil with ether or alcohol, dry out excess solvent, immerse the fibres in the acidified bleaching powder solution for thirty seconds. Shake off the excess solution, rinse with alcohol and partly dry the fibres. On exposure to ammonia fumes, manila fibres are colored brown. All adulterant fibres are cherry red.

28. Technical Terms.

Yarn	Fibres twisted together
Thread	Two or more small yarns twisted together
String	Same as thread but of larger yarn
Strand	Three or more large yarns twisted together
Cord	Several threads twisted together
Rope	Several strands twisted together
Hawser	Large three-strand rope
Cable	Three hawsers twisted together

A rope is

Laid	By twisting strands together
Spliced	By joining to another rope, by interweaving the strands
Whipped	By winding yarn or small stuff around the ends
Served	When wound continuously with yarn or small stuff
Parceled	By wrapping it with canvas
Seized	By binding two parts together with yarn or small stuff
Payed	When painted, tarred or greased

CHAPTER II

WIRE ROPE

29. General. Fibre rope is made by twisting together the small and comparatively short fibres of manila or other rope making material. Wire rope, on the other hand, is made by twisting together wires of suitable size that extend, unbroken, from one end of the rope to the other.

Wire ropes used for hoisting, haulage and transmission purposes are usually made of steel wire; iron is often used for wire but seldom for rope. Iron does not rust as quickly as steel and takes tinning and galvanizing better.

When electrical conductivity is a factor cables are made from copper, bronze or aluminum. When strength and conductivity are both important, duplex ropes and cables are used having a copper or aluminum core surrounded by a covering of steel wires.

Steel of different grades is the common wire rope material for engineering purposes. The following common trade names are given to different classes of steel wire used for rope making.

0.1% to 0.3% carbon is soft steel wire.
0.3% to 0.6%, cast steel wire.
0.6% up, plow steel wire.

These are trade names and should not be confused with the ordinary qualities of steel. The better grades of steel wire are made from steel very similar to the ordinary crucible steel, but are usually the product of an open hearth furnace. Alloy steels are not used to any great extent on account of the difficulty of cold drawing, cost and lack of uniformity.

30. Wire. Wire is made from wire rod. Wire rod is rolled from steel ingots and is from $\frac{1}{2}$ to $\frac{3}{8}$ of an inch in diameter. Great care must be taken in pouring the ingots. They must be uniform in quality, free from blow holes, segregated spots, slag and other imperfections. The ingots must be carefully cropped below any possibility of pipe. Any small imperfection in the ingot will be drawn out along the wire rod and when this is drawn into fine wire, the bad place may extend a great many feet and make up a large proportion of the cross-section of the wire. The wire rods, when they come from the rolls, are covered with mill scale, and must be cleaned by pickling. The acid is then removed with lime and the rods are lubricated with talc or some similar substance. The wire rods are now drawn cold through draw plates, having holes of diminishing diameter, and after each pass are reeled. The amount of reduction and consequent lengthening that can be obtained before the wire becomes too hard for further drawing varies with the composition. When this condition arrives, the coils are annealed very carefully and the drawing continued, using the softened wire. The final physical condition, as regards size and strength, determines the number of drawings and annealings. The smaller a hard drawn wire is, the harder it may be, and still have sufficient flexibility. An extremely strong and flexible rope must be made from a large number of small wires of fairly high carbon content, drawn to a hardness, limited only by the necessary flexibility required for construction and ability to run over the required sheaves or pulleys.

Testing of Wire. Wire is tested in tension, torsion, and bending, the methods being carefully standardized. It is a curious fact that the apparent modulus of elasticity of a hard drawn steel wire is often less than that of the same wire annealed, due to the initial strains set up by cold drawing.

31. Wire Strands. Common wire strands are made by twisting layers of wire about a single central wire in a stranding machine. A great number of different strands are used in rope making, the most common being: —

One central wire with a layer of six wires around it, *seven-wire strand.*

7 wires 19 wires 37 wires

61 wires 91 wires

FIG. 1. — Wire Strands.

Add another layer of twelve wires, making a *nineteen-wire strand.*
Add another layer of eighteen wires, making a *thirty-seven wire strand.*

Add still another layer of twenty-four wires, making a *sixty-one wire strand.*

And finally another layer of thirty wires, making a *ninety-one wire strand.*

The flexibility of a strand depends upon the number and size of the wires entering into it; the smaller the wire the more flexible the strand.

32. Wire Rope. There are many kinds of wire rope made for special purposes. Only the most common will be taken up here.

Haulage rope, six strands with seven wires each, with central core, 6 × 7.

Hoisting rope, six strands with nineteen wires each, with central core, 6 × 19.

Special flexible hoisting rope, six strands, thirty-seven wires, with central core, 6 × 37.

Extra flexible hoisting rope, eight strands, nineteen wires, with central core, 8 × 19.

The cores in wire ropes are made of fibre and usually carry considerable lubricant.

Tiller and other extremely pliable ropes are made from a number of ordinary ropes with their cores, all twisted about another central core.

Haulage Rope

Hoisting Rope

Special Flexible Hoist Rope

Extra Flexible Hoist Rope

Tiller Rope

FIG. 2. — Common Wire Rope.

The function of the core is to furnish a foundation for the wires to press upon when the rope is stretched and also to furnish lubricant.

33. Construction. *Plain Lay.* The wires are twisted into a strand in one direction and the strands twisted into a rope in the opposite direction.

Cable Lay. Small ropes twisted into a cable in the opposite direction from the twist of the strands in the small rope.

Langs Lay. The wires in the strands and the strands in the rope are twisted in the same direction. This construction furnishes a smooth wearing surface, but the rope will untwist more easily than the plain lay and cannot be easily spliced.

In ordinary rope all the wires in the various strands are of the same size, with the possible exception of a central wire.

Warrington Type Rope. The strands are made up of three sizes of wire.

Seale Type Rope. The strands are made of two sizes of wire.

These two constructions produce a slightly more compact rope than in the case where the wires are all of the same size.

The strength of a wire rope depends upon the strength of the component wires. When these component wires are hard drawn, it is necessary that they be small in diameter. The flexibility of a rope depends on the diameter of the wires and the number of cores. An extremely strong and flexible rope will have a comparatively small central core and be made up of six or eight strands, each in turn being formed of a large number of extremely hard drawn wires of small diameter. The addition of extra cores will increase the flexibility at the expense of the strength.

34. Special Ropes. *Non-spinning rope* is made by twisting a certain number of strands in one direction in the inside of the rope, and covering them with a layer of strands twisted in the other direction, the strands being so designed as to balance each other.

Steel-clad Rope. The strands are covered with a flat steel armor.

Durable Rope. Strands are covered with fibre.

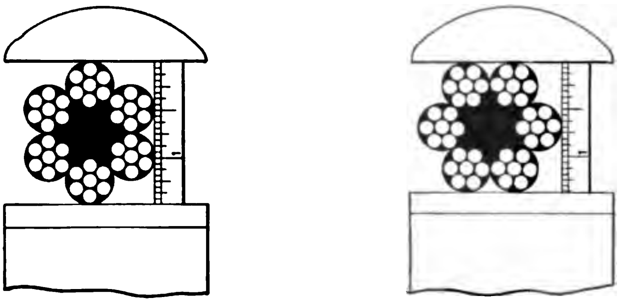
Flat Rope. A number of small ropes placed side by side and laced together.

35. Manufacture. Wires are formed into strands on a wire stranding machine. The strands are closed into a rope on a rope closing machine. Great care must be taken to keep the tension of all wires and strands equal.

36. Size of Rope. Wire rope is always specified by diameter, measured as large as possible (Fig. 3).

37. Rope Fastenings. The strength of a rope depends upon the fastening. In using loops or eye splices, the rope should always be passed around a thimble to prevent injury to the small wires. An eye splice properly made is often 100 per cent efficient, whether seized or not. A long splice properly made on a medium sized rope is nearly 100 per cent efficient.

Clips and Clamps. These are the usual methods of fastening rope. Great care should be taken to place the clips on correctly. Clamps are usually grooved to fit the rope and care should be taken to see that the twist of the rope fits properly in these grooves. The efficiency of clips and clamps varies greatly.



Right Wrong

Fig. 3. — Measurement of Wire Rope.

Wrong

Right

Fig. 4. — Use of Clamps.

Sockets. A great many kinds of sockets are used. The end of the rope must be opened out, the wires straightened and cleaned, then pulled down into the socket, which is filled with type metal, tin or some other similar composition. The cores should be cut out and replaced with metal.

Great care should be taken to keep the heat in the soft metal below the temperature which will anneal the small hard drawn wires. The socketing of a large many stranded rope is a rather difficult job. Many small wires and ropes may be held in highly efficient fastenings either with or without solder.

38. Testing of Wire Rope. Tests are usually made for tensile strength. The only trouble met with is in holding the ends in the testing machine. In a small rope or one made of fairly soft wires, the ends may be cast in a hole in a wooden block and the resulting metal cylinders held in the jaws of the testing machine. Large and pliable ropes must be held in special sockets, great care being taken in the casting. Compound sockets are sometimes used and in some cases special clamps or drums serve the purpose. The modulus of elasticity of an ordinary steel wire rope is not far from twelve million pounds per square inch after it has become set. It should be noted that a wire rope is very different in construction from a fibre rope and in many case its efficiency, figured on the strength of the component wires, is over 90.

Wires for ropes may be protected by galvanizing or tinning. The galvanizing usually offers the best protection.

39. Handling of Wire Rope. Great care should be exercised in coiling and uncoiling wire rope. The coil should be rolled along the floor to uncoil the rope or if on a reel a bar should be passed through the hole in the reel and the rope pulled off from the reel as it revolves. The sheaves or pulleys upon which a wire rope runs should be of ample size and sudden reverse bends should be avoided. Wire ropes that are used out of doors should be protected by a coating of lubricant.

SECTION 9

MECHANICAL FABRICS

1. Mechanical Fabrics. The development of the modern aircraft and automobile has brought into prominence many engineering materials, the character and worth of which have never before been fully appreciated. Foremost among these are new forms of woven fabrics, which by their lightness, strength and flexibility fill a very important part in the construction of wheel tires, gas bags and wing coverings. In addition to these new uses are the more familiar ones, namely: in hose, belting and similar mechanical developments where the strength is secured by the vulcanization of some textile material into the structure.

The classes of fabric of most interest to engineers may be listed as follows:

(*a*) Tire fabric for wheel tires.
(*b*) Balloon fabric for kites, dirigibles and balloons.
(*c*) Wing fabric for aircraft wings.
(*d*) Canvas for belting.
(*e*) Canvas for hose pipe.

Certain very essential characteristics of the fabric are necessary to satisfy the requirements of the particular use. Rubber is not employed in combination with the fabric in all of these forms. For airplane wings, on account of the probable presence of gasoline, the use of rubber is prohibited. Therefore, the wing of the airplane has to rely upon some other substance, such as the various chemical dopes, to enhance its strength and make it impervious to the passage of air.

2. Characteristics of Mechanical Fabrics. In reviewing the necessities of the fabric base for the above uses, it is evident that certain characteristics must be sought and adhered to rigidly. These are listed in general as follows:

(*a*) Strength and lightness.
(*b*) Flexibility and toughness.
(*c*) Breadth of supply.
(*d*) Ease of procurement.
(*e*) Cheapness.
(*f*) Moisture absorptivity.
(*g*) Gas tightness.

The relative value of these characteristics depends upon the particular use to which the fabric is put. In general, strength is a prime requisite. In most of the uses of mechanical fabrics, lightness is desirable. This is especially true in regard to aeronautical work, and is of considerable importance with regard to wheel tires. All of the above uses embody repeated stresses, therefore, flexibility and toughness are of very great importance. Certain fibres, notably cotton and silk, possess great flexibility, and will stand for long periods of use in such mechanical members as those listed above. Brittleness of a textile fibre is an undesirable attribute, leading to failure with but little warning. For this reason, many otherwise desirable fibres, such as ramie, would rarely be used under repeated stresses.

In order to make the fibre of broad use in mechanical lines, its production should be well scattered over the face of the earth. This was especially noticeable in the recent world war where the zone of hostilities enveloped a very large percentage of the agricultural area devoted to the production of linen. For this reason other forms of wing fabric had to be sought. If a fibre is to be important commercially, its procurement should be easy, crops should rarely fail and its production should not be accompanied by any very complicated processes. Except for the ravages of insects, cotton is comparatively sure of harvest. In the case of linen, however, the processes of retting, which are carried on coincident with the harvest of the flax straw, are not always attended with complete success; and thus the flax fibre is injured and rendered of low grade. The same is true, in a measure, of ramie and various other textile fibres.

The part which moisture plays in the strength and use of mechanical fabrics is very important. Most fibres are highly hygroscopic, absorbing automatically a large percentage of their total weight in the form of moisture. In the case of most vegetable fibres, this enhances the strength; in the case of animal fibres, there is generally a mild diminution in strength. Whether this moisture absorption penetrates to the interior of the individual fibre, or, condensing upon its surface, increases its adherence to other fibres, is as yet a matter of dispute. The " porousness " of many fibres is notable. Especially is this true of linen. Not only does the flax fibre absorb large amounts of moisture automatically, but it " takes " chemical dopes and cloth varnishes with avidity; and is, therefore, a very desirable fabric to employ in this connection. In general the absorption of moisture is of small importance in regard to the actual use of the fabric; but it is very necessary in order to fill specifications regarding strength to know exactly the moisture condition of the fibres when tested.

For those fabrics especially employed for the retention of gasses of the character of hydrogen, the tightness is of paramount importance. " Rubberization " is always employed in this connection to make the gas bag as impervious to the passage of the hydrogen as possible. The test for permeability is generally performed by submitting the rubberized fabric to an atmosphere of hydrogen under definite pressure. The gas which percolates through the retaining wall is burned with an excess of oxygen and the resulting water vapor collected and weighed. This gives a means of determining the permeability of gas bag fabrics in terms of liters of hydrogen at given pressure and temperature.

3. Fibres Employed.

- (*a*) Cotton.
- (*b*) Linen or flax.
- (*c*) Silk.
- (*d*) Ramie.
- (*e*) Kapok.
- (*f*) Hemp, Manila and Jute.

Probably cotton will become the ultimate material for mechanical uses. It fulfills more of the above listed desirable characteristics than any other textile fibre. In immaturity, it consists of a circular tube, adhering at one end to the seed of the cotton plant. At harvest the tube hardens and collapses, so that its cross-section resembles a figure eight. The outside of the fibre is covered with a wax peculiar to the plant. The length or " staple " varies from about five-eighths of an inch in inferior grades of cotton, especially those grown in dry regions, to one inch and a half and sometimes one and three-quarter inches in the case of " Sea Island " cottons. The latter are raised in close proximity to moisture and are finer, stronger and spin better than " uplands " cotton. As the fibre matures, it not only collapses in structure but takes on a certain degree of spirality; Fig. 1. Thus the " hook " or " cling " of the fibre renders it comparatively easy to spin and increases the strength of the product. Various other fibres are inherently stronger than cotton, but they are generally lacking in spirality and thus fail to make as strong or as flexible yarn.

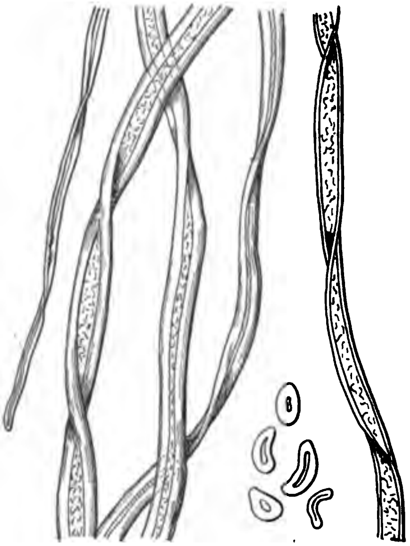


FIG. 1. — The Cotton-fibre. (After Hassack.) 200 Diameters.

In certain portions of Europe, especially Belgium, France and Ireland, the soil and climate are well adapted to the growing of flax. The plant stands from twenty-four to thirty inches in height, and is known as flax straw. After cutting near the root, it is bound into small bundles and immersed for a period of some days in the sluggish water of ponds or slow moving rivers. This process, known as retting, has for its object the decortication of the flax straw and the release of the fibre which lies just under the bark. After twelve to fifteen days, the bacteriological action has been completed, and by the odor and appearance the flax straw is ready to be removed from the water, stacked and dried. This is generally accomplished by the natural means of the sun and air.

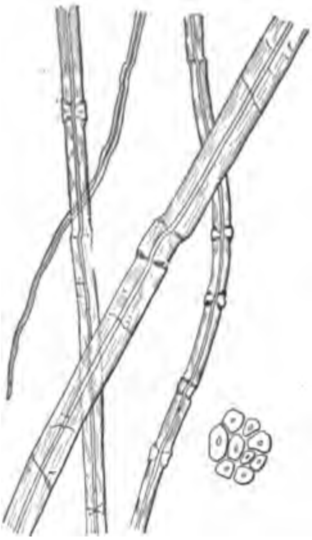


Fig. 2. — The Flax-fibre. (After Hassack.) 200 Diameters.

Most of the manufacturing processes in connection with flax are of primitive character: thus the flax straw after retting is "hackled" or "lashed" over boards filled with protruding nails, whereby the wooden core of the straw is shaken out and the released linen, or "line" fibre remains. Under the microscope, Fig. 2, the flax fibre resembles somewhat the stock of the bamboo, having across its structure at frequent intervals nodes, or partitions, similar to the bamboo. It has but little hook, and spins, especially in fine yarns, with comparative difficulty; but it is inherently very strong, is porous and absorbs chemical preparations with ease and uniformity.

On account of the cost, the product of the silk worm, Fig. 3, is rarely put to mechanical uses. It is totally different in its structure from that of linen or cotton. At the end of its life the silk worm spins a continuous double thread, cemented together with a wax secreted by itself. This cocoon may run as long as 1200 yards in practically a continuous fibre. The cocoons are unwound with as much care as possible and the individual strands combined into yarns of the size desired for the particular fabric. Silk of this form, known as

Fig. 3. — Silk. (After Hassack.) 200 Diameters.

" organzine," is not put through operations of carding or other combing, but is " thrown " or doubled to the desired degree, the fibre being practically continuous. If the cocoons are submitted to an operation which tears the fibre into shorter lengths and combs it to parallelism and uniformity, the product would be classed as " floss " silk. This is less expensive and of much less strength than the genuine organzine fibre. The silk fibre is inherently very strong and has been used to a limited degree for mechanical purposes.

FIG. 4. — Ramie. (After Hassack.) 200 Diameters.

Ramie, or China grass, Fig. 4, is somewhat similar to linen in its production and manipulation. Its growth is mostly confined to India and China. It is sometimes released from its wax by mild caustics which often injure the fibre. In its best form, ramie is very strong, but under the microscope it is evident that the fibre has but very little spirality. It is correspondingly hard to spin and does not make as strong yarn as cotton. From its " inflexibility " its use is limited. In the form of gas mantles, it has a very wide adaptability; but is practically never employed for fabrics under repeated stresses. Attempts have been made to employ ramie for sail fabrics, but its lack of felting qualities render it unfitted for this purpose.

Certain other fibres which grow upon the seeds of the Bombax tree in tropical countries should be listed as mechanical fibres. These are generally included in the term " Kapok " fibres. They are rather short and tubular in structure and have no spirality. Attempts to spin them into yarn have not met with success. From the comparatively large amount of air contained within their structure, these fibres are very valuable as a medium of bouyancy for life belts and mattresses.

Manila, jute and hemp are rank vegetable growths, the fibres of which are released in much the same manner as linen. These fibres attain great lengths, in the case of Manila sometimes reaching fifteen feet. The product, which is heavy and strong, is employed only for ropes or cords.

Cotton and Kapok fibres are attached to the seed of a plant and for that reason are sometimes called " beard " fibres. Linen, ramie, Manila, hemp, jute and sisal, which are encased beneath the bark of the plant, are termed "bast" fibres and are essentially different from the beard fibre in character.

4. Manipulation of Fibres in Manufacture. The fibre chosen must be thoroughly cleansed of dirt and foreign matter and arranged with the highest degree of parallelism. The placing of the fibres in parallel order and the exclusion of those below a certain grade of length is accomplished by the operations of carding, drawing and combing. These processes are therefore of paramount importance in the production of a satisfactory mechanical fabric. Next, the weft must be attenuated or drawn down to the desired size of yarn, and the spinning operation must be carried out with as much precision as possible. In certain processes where the object is to produce a fabric with as little stretch as possible, mercerization has been resorted to. The immersion of cotton fibre in mild caustics, followed by washing and drying under tension, imparts to the fibre a fine hard finish which appears as a luster in the finished product. At the same time the "stretchiness" of the yarn or fabric is very much reduced, and the finished goods absorb dopes and dyes with much greater avidity. Mercerization is rarely employed in heavy mechanical fabrics, since the gain is not of sufficient importance. Lastly, the yarns are woven into the simplest kind of fabric, namely: one thread up and one thread down in alternation. Many attempts have been made to knit the fabric to the special form which it is to take, but on account of the number of bends in the yarn, these processes have not so far met with success.

5. Character of Yarn. The size of yarn is indicated either by the English or Metric system. In the English system of numbering, the unit is the hank of 840 yards. When one hank weighs one pound, the yarn is "No. 1:" thus the number of hanks per pound constitutes the number by the English system. To obtain the number of any unknown portion of yarn, one skein of 120 yards is generally reeled off and weighed in grains. Considering that there are 437.5 grains per ounce, or 7000 grains per pound avoirdupois, it is easy to reduce the yarn to its corresponding number. In the metric system the skein is 1000 meters in length, and when this length weighs one kilogram, the yarn is said to be "No. 1." Occasionally in foreign specifications metric numbers of yarns are met with.

6. Conversion Factor. It is often convenient to convert English numbers into Metric by a single arithmetical operation. The relation between the two systems is determined as follows:

$$\begin{aligned} 1 \text{ kilogram} &= 2.205 \text{ lbs.} \\ 1 \text{ meter} &= 39.37 \text{ ins.} \\ 1 \text{ metric skein} &= 1000 \text{ meters} \\ &= \frac{39{,}370}{36} \text{ yds.} \end{aligned}$$

$$= \frac{39{,}370}{36 \times 840} \text{ hanks}$$
$$= 1.302 \text{ hanks.}$$

Then the conversion factor to change English numbers to Metric is

$$= \frac{1.302}{2.205}$$
$$= 0.59$$

Therefore, to change English numbers to Metric, divide the former by 0.59. Thus 28s. (English) equals 47.47s. (Metric).

7. Plied Yarns. When more than one elementary yarn is combined to form the finished yarn just before weaving, the material is denoted as "plied." The direction of twist is indicated by Fig. 5. The yarn is rendered much stronger and evener by this method of manufacture, but the expense is considerable.

8. Cabled Yarns. When the utmost strength combined with lightness is desired, the process of plying is carried one step further, namely: the original plied yarns are plied again. The structure of such yarns is shown by Fig. 6. It is apparent that the direction of the twist cannot be reversed twice in the manufacture of such yarns. Therefore, it is carried out as shown by the arrows. These cabled yarns or " cords " are those used in the manufacture of the various " cord fabrics " as applied to automobile tires. They are expensive to construct, must be laid with great precision, but when carefully manufactured are very strong and flexible.

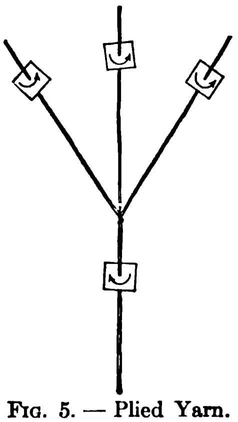


Fig. 5. — Plied Yarn.

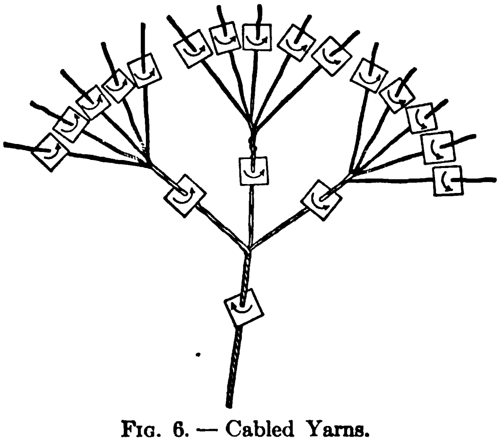


Fig. 6. — Cabled Yarns.

9. Twist Rules. The amount of twist to embody in yarn in order to gain its maximum strength has furnished an almost endless source of experiment and controversy. It is evident that too loose a twist will cause weak yarn, while too many twists per inch will injure the strength of the product. Twist rules generally take the form $T = C\sqrt{No.}$ Where T is the twist per inch, C is a constant depending upon the character and use of the product, and the quantity under the radical is the number of the yarn. This constant varies from four to five, in the case of fine hard twisted yarns, down to about 1.2 in soft rovings where subsequent drawing operations are yet to take place. The usual twist rules are tabulated as below; but it must be understood that spinners make wide variations from this table to suit their own ideas and products.

Standard Twists per Inch of Length

English standard for roving	$1.20\sqrt{No.}$
American standard for roving	$1.28\sqrt{No.}$
Yarn	
Ordinary frame warp	$4.75\sqrt{No.}$
Medium frame warp	$4.50\sqrt{No.}$
Extra Mule	$4.00\sqrt{No.}$
Ordinary Mule	$3.75\sqrt{No.}$
Ordinary Mule Filling	$3.25\sqrt{No}$

In the case of plied and cabled yarns, the twist is generally chosen so as to "balance." A piece of the product about a yard long with its ends held in two hands may be allowed to droop and finally have its ends brought together without any tendency of the loop of yarn to kink or twist. This balancing of the twist is generally found by experiment to fit the particular case of plied or cabled yarn.

10. Character of Fabrics. For mechanical fabrics, plain weaves are generally employed; the threads being raised and lowered in regular alternation by the loom for the passage of the shuttle. The threads which run lengthwise of the cloth in the loom are called warp, while those placed cross-wise by the shuttle are called weft or filling. In order to shape the fabric accurately, a number of extra threads must be added at the sides, thus forming the selvages. To be certain, therefore, of the direction of warp and filling, a piece of the selvage edge should be included with the test specimen of fabric.

The weight of the fabric is very frequently increased by the addition of foreign matter to the yarn. This may take the form of a legitimate sizing or "slash" necessary to make the warp threads resistant to the wear of the harness in the loom; or it may consist of working into the fabric various compounds of white earth, lead etc., with the object of changing its appearance and increasing its weight. The latter procedure is generally classed as an illegitimate sizing or weighting of the fabric. Such manipulations have no place in mechanical fabrics and the amount of sizing present should be kept to a very small figure, if any is permitted. Heavy fabrics for tires and belts are not generally slashed; and in the case of the finest wing fabrics and balloon cloth, the sizing is generally limited to 3½ per cent of the original weight. Occasionally the plying of the product is accomplished in the fabric form rather than in the yarn. Such fabrics are known as plied fabrics, Fig. 7. They consist of combining two or more layers of fabric, generally with the direction of the threads at 45 degrees to one another in the subsequent layers. The whole is then vulcanized into a unit fabric. The object of plying the fabric is to gain the maximum of strength with the minimum of weight. The reason for laying the biased ply in balloon cloth, as shown in Fig. 7, is in order that tears may be localized and not follow the thread and run, as would be the case in single fabrics. Balloon fabrics, gas holders and similar products are generally plied fabrics.

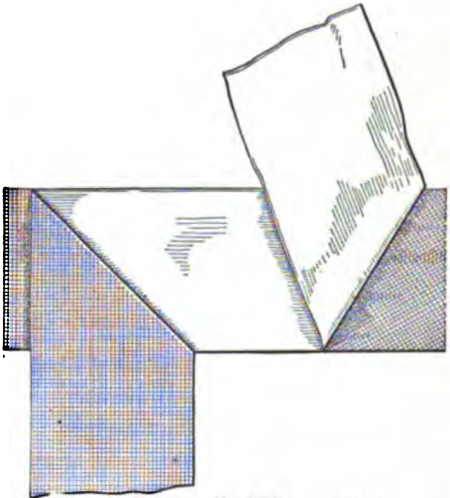


FIG. 7. — Two-Ply Balloon Cloth.

The modern adaption known as cord fabrics, Fig. 8, consists of laying warp-wise cords in parallel order and running through them a very light single filling yarn for purposes of assembling only. Thus the filling in

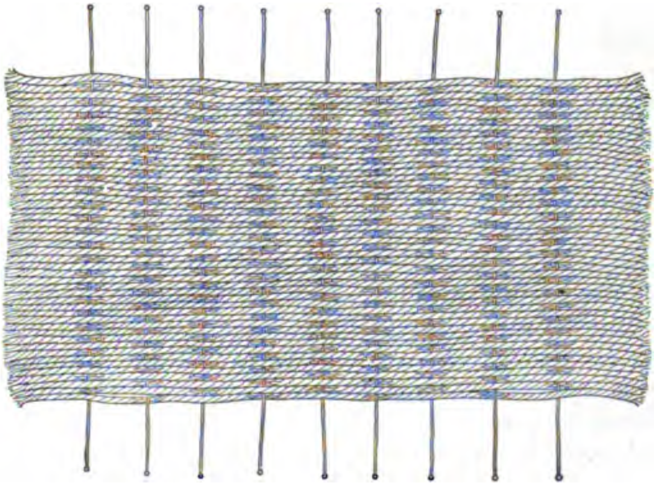


FIG. 8. — Cord Fabric.

cord fabrics is merely an incident designed to preserve the form of the fabric till placed in the tire but not in any way to add to its strength. Such cord fabric when rubberized and vulcanized in many pliés forms the most modern type of automobile tire. In the case of the simple weave, or " square " tire fabric, Fig. 9, the warp and filling threads cross one another in alternation. Under the vibration of use upon the road the threads would probably cause the destruction of one another where they cross after a comparatively short interval of use. In the case of the cord fabric, the layers are plied at 45 degrees or 90 degrees with one another but the individuality of each layer of cords surrounded by a medium of rubber is preserved to a considerable degree, and there is but little tendency for it to destroy the neighboring plies from internal stresses.

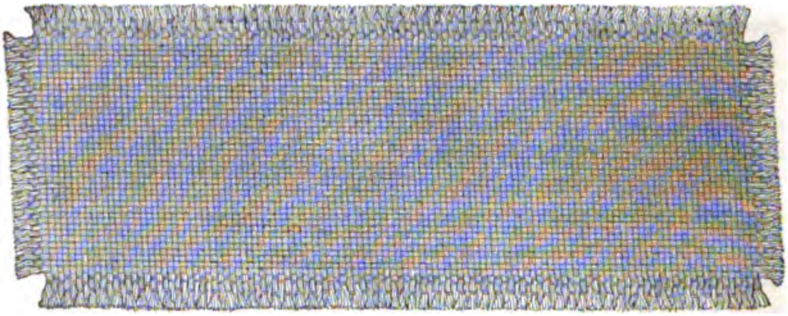


Fig. 9. — Square Woven Fabric.

11. Crimp. It is evident in a plain weave that the final form of the warp and filling threads is of much consequence in the ultimate strength of the fabric. If the warp threads are practically straight, while the filling threads are very tortuous, as they lie in the fabric, any external load, such as those imposed upon a tire upon the road, would be resisted largely by the warp threads alone. If these fail, the load will be thrown upon the filling threads. Thus the fabric would not resist equally in warp and filling any liability to rupture. On the other hand, if the warp and filling threads were applied or placed in the fabric in such a manner that each deviated equally from a rectilinear position, then the warp and filling threads would share equally any external load. A fabric so built is known as " square," and is the desirable form for most mechanical uses. In case the stress is always to be in one direction as in belting for instance, the warp or lengthwise threads should be as straight and strong as possible, while the filling threads would have but very little load to sustain. When a fabric is out of balance, namely: when there is a much straighter set of threads in one direction than another, the fabric is known as " off-square." The determination of crimp has come to be regarded as a very important piece of data in regard to most mechanical fabrics.

Definition of Crimp of Fabric.

> "Crimp shall be defined as the difference between any two points on a yarn in a fabric and the same two points after the yarn has been removed and straightened. This length shall be reduced to percentage of the yarn length as it lies in the fabric. The percentage of warp crimp minus the percentage filling crimp shall be defined as the off-square of the fabric."

12. Method of Testing Crimp. The American Society for Testing Materials has made an extended study of the best method for determining the crimp of mechanical fabrics as defined above. The method proposed for square woven tire fabric is described as follows:

> "Threads for crimp test of tire fabric shall be taken from the inside edge of test piece as near the center line of the roll as possible. Threads for crimp test shall be laid out by marking across them in the fabric parallel lines not less than 6 inches apart. An even number of threads not less than four in number shall be taken for each warp and each filling test. These threads shall be ravelled from the fabric after marking, allowing 2 inches extra on each end of the threads beyond the marks. The threads shall then be straightened by a machine which applies a constant load of 75 grams and the length between the original markings shall then be read in terms of the yarn length as it lay in the fabric. The machine shall be equipped with a dial or scale so arranged as to read the percentage crimp directly."

There has been much discussion as to whether the crimp should be rated in percentage of the yarn length after straightening or of the yarn length as it lies in the fabric. At present the latter has been accepted but there are still many manufacturers who calculate the crimp percentage in terms of the straightened yarn.

It is necessary in using the crimp tester to know with accuracy what weight should be employed to straighten the yarn but not to stretch it. Mr. Walen of the Bureau of Standards proposed a method for the determination of this weight by plotting a stress-strain diagram for a piece of ravelled yarn. When the diagram becomes a straight line the crimp has been removed and the yarn is stretched. A different weight must be used for each kind of fabric.

13. Testing Fabrics for Tensile Strength. The effect of moisture is of very great consequence in the ultimate strength of fabrics. Vegetable fibres in general increase while animal fibres decrease in strength due to the absorption of moisture. This increase in strength does not play any part in the " engineering " of the fabric, but is merely an item in tests and specifications which is of very great importance. For instance, a certain fabric may be in the machine upon a moist day and show comparatively high strength; and again, upon a cold winter day with low humidity conditions would show a decided falling off in strength. Unless this is thoroughly taken into account, specifications and tests are of but little importance. The increase in strength due to moisture or " regain," as it is generally phrased, ranges from 20 or 25 per cent of the dry strength in the case of certain light fabrics to over 100 per cent increase in heavy fabrics. The testing of fabrics, therefore, must proceed from the standpoint of moisture treatment. There are three general methods used in tests:

(*a*) Bone dry.
(*b*) Under standard atmospheric conditions.
(*c*) Corrected for moisture present.

(*a*) The fabric samples are placed in an oven under uniform temperature slightly above the boiling point of water for a period of about two hours. The oven, meanwhile, must be ventilated so that not only will the moisture be dissociated from the fabric but removed. The samples are then taken as rapidly as possible from the oven, inserted in a testing machine and broken. The difficulty with this method is that a bone-dry fabric in passing through a more or less moist atmosphere outside the oven will take on moisture with tremendous rapidity, its strength increasing with the length of interval between the oven door and the testing machine. The method is not very satisfactory. The slower the operation the greater will be the apparent strength. Comparatively few specifications are at present written in terms of bone dry strength.

(*b*) Apparently, the most satisfactory method of testing textiles is to subject them for moderate periods of time to an atmosphere of known temperature and humidity. This " standard atmosphere " has been defined by the Bureau of Standards as having:

A temperature of 21.1° C. (70° F.).
A relative humidity of 65 per cent.

It is comparatively easy and inexpensive to install apparatus which will raise the natural conditions of the atmosphere to the above limits and hold them there with considerable accuracy during the winter; but during the summer months the natural humidity generally exceeds the above limits and expensive and complicated dehumidifying apparatus is necessary if the tests are to be carried out with precision. There are many laboratories in the country where conditions of temperature and humidity can be raised to the above standard and held there with precision. On the other hand, aside from the Laboratory of the Bureau of Standards in Washington and a few private laboratories, there are very few places where an accurate reduction of temperature and humidity may be obtained. For the above reasons, the testing of textiles under standard atmospheric conditions, while very desirable, is filled with difficulties. It is not enough simply to raise the moisture to a high percentage and hold it there, as is sometimes done in testing rooms, since the results so obtained will be artificially high and irregular. Textile testing should be confined to winter months when definite conditions may be easily secured or else the necessary refrigerating apparatus should be at hand to lower the humidity and cool the testing room.

14. Moisture Corrections. It is apparent that every fabric follows a certain law of variation in strength with relation to the moisture. This relation has been plotted very definitely by many laboratories. For instance, for square woven tire fabric the increase in strength is practically 7 per cent for each single per cent of moisture above bone dry. The plot of the behavior of the fabric is slightly curvilinear but through the regions practically found in testing rooms the plot is practically a straight inclined line of the character specified in the above figures. Therefore, if a laboratory is working exclusively upon square woven tire fabric, it is comparatively easy to deduce an arithmetical table whereby the apparent strength in the machine may be corrected, either to a bone dry basis or one of high regain, by measuring the exact amount of moisture in the fabric at the time of the test. This latter method is one which is rapidly increasing in use. The fabric taken from the roll or piece is cut to the desired shape, hung in the testing room to secure uniformity and then tested. Immediately upon breakage, the ruptured specimens, either singly or with a fair number combined, are enclosed in airtight capsules and weighed. The reason for the capsule is to make sure that the moisture content does not change while the weighing operation is in progress. The broken samples are then dried in an oven and weighed again, and the difference between the two weights, reduced to percentage of the " bone-dry " weight, is the actual regain present at the time of the tests. By consulting an arithmetical table under this figure of regain, it is very easy to transfer or correct the apparent reading of the machine to that either at bone dry or any specified figure of regain. This method has been adopted by many tire companies and others and appears to be the best way in which to handle the troublesome question of moisture in fabrics.

15. Shape of Specimen. There are two general methods of cutting the specimens for tensile test. First the " strip" and second the " grab " method. In the strip method a piece of the fabric either 1¼ inches or 1½ inches wide is cut about 10 inches long. The side threads are ravelled out to a depth upon each side sufficient to give a net width of one inch to the specimen. The reason for this is that if a textile specimen is pulled when cut to the net desired width, the side threads will ravel out of the fabric. Consequently their length will be increased and the body of the specimen will break first and later the outside threads. This method is therefore under the criticism that it does not give the uniform breaking strength across the fabric for a width of one inch. However, if ravelled as above stated the effect of the elongated side threads is as near negligible as possible.

The preparation of such specimens for textile testing consumes considerable time. It has therefore been suggested, and adopted to a certain extent, that specimens of the fabric to be tested shall be cut about 5 inches long by 2 inches wide. The jaws of the machine are made one inch square and are clamped into the body of this piece of fabric at a distance apart of one inch. This is designated as the " grab test." There is no ravelling of any threads, but the criticism is that the adjacent areas of the cloth reinforce the piece on which the tension is actually existing. From many tests made it is fairly well established that the " strip " method gives the more uniform results while the " grab " method gives higher figures and at the same time more divergent results.

16. Location of Specimens. In order to test fairly care should be taken that the same set of warp threads or filling threads do not exist in any two test pieces. It is therefore incorrect to cut a series of either warp or filling specimens end on end since the same set of threads is being broken over and over again.

17. Jaw Speed. It is fairly well established that in tensile tests on textiles comparatively few individual fibres are broken. On the contrary, the frictional hold of the fibres upon one another is overcome by the tension and slipping results. Therefore the more rapid the test the greater the apparent strength of the textile. There exists at present a wide divergence of practice in regard to the speed of the pulling jaw. There is naturally an inclination on the part of manufacturers to use as high a speed as possible so as apparently to enhance the tensile strength of their product. On the contrary such high pulling speeds vitiate the results of stretch recording apparatus and increase the inertia errors in the testing machine. The Bureau of Standards has proposed 12 inches a minute for the speed of the pulling jaw. This figure has been widely adopted. Certain manufacturers have chosen 20 inches, and in a few cases 24 inches per minute as the speed of the pulling jaw. The apparent strength of any textile can be caused to vary some 30 per cent by this item alone.

18. Testing Apparatus. The yarn reel, oven, balances, textile micrometer and tension machines comprise the apparatus most generally used for textile testing. The yarn reel is 1½ yds. in hexagonal circumference, therefore 80 " threads " or " rounds " will reel one skein of 120 yards.

The electric oven is provided with a thermostat and magnetic switch so as to hold very closely to a desired maximum temperature. This is generally set from 104° to 110° C. (220° to 230° F.). Cotton fabrics can be dried at this temperature for periods of 15 or 20 hours if necessary without injuring their composition.

The chemical balances should read with a precision of one hundredth of a grain in order to secure the third significant figure in regain measurements and similar work.

The tension machines are usually of the pendulum type and may be provided with a stretch recording apparatus by means of which the elongation of the specimen may be registered automatically with the load in pounds which it took to produce it. The accuracy of these machines is very close and the inertia errors are not more than 2 per cent.

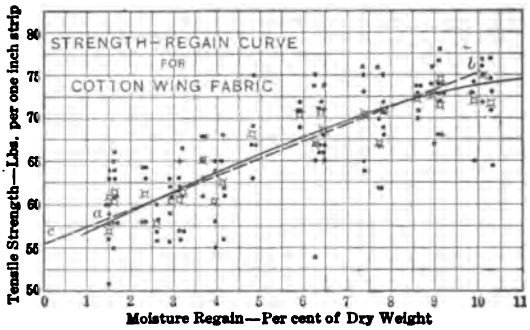


FIG. 10. — Strength — Regain Curve for Cotton Wing Fabric.

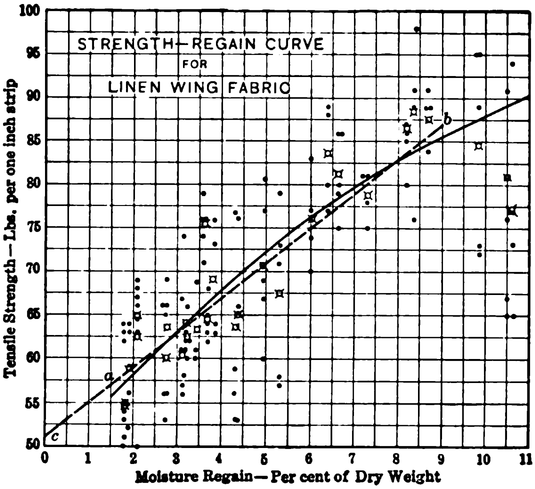


FIG. 11. — Strength — Regain Curve for Linen Wing Fabric.

19. Moisture Control. The control of moisture in the testing room, as mentioned previously, is of paramount importance. Various forms of spray heads are used for atomizing water into the atmosphere of the testing room. In connection with these the control instrument or psychrostat is used to control the humidity. The spray-heads will rapidly raise the condition of the air to a certain predetermined limit. The psychrostat takes a continuous sample of the room air and at the desired point of humidity shuts off the action of the spray head; thus the apparatus is largely automatic. Figs. 10, 11, 12, 13, illustrate the behavior of fabrics in regard to tensile strength as the moisture increases. It is evident from all of these plots that correction tables can be easily calculated for any kind of fabric.

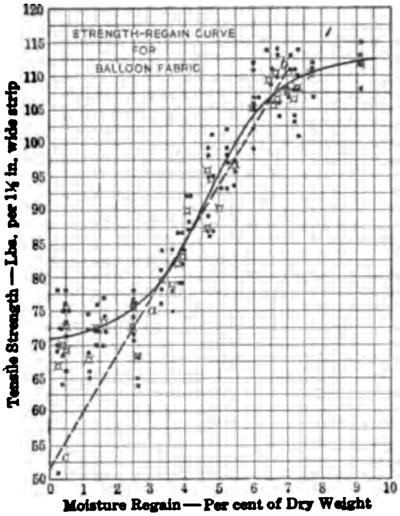


FIG. 12. — Strength — Regain Curve for Balloon Fabric.

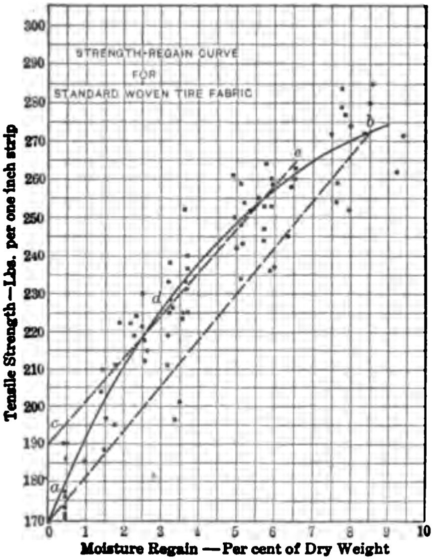


FIG. 13. — Strength — Regain Curve for Standard Woven Tire Fabric.

20. Strength Variation in Terms of Fabric Weight. It has long been conjectured that the effect of the moisture in increasing the tensile strength was of more consequence in heavy fabrics than in those of gauze-like structure. Fig. 14 shows a series of tests made in the laboratory of the Massachusetts Institute of Technology upon various classes of fabric varying in weight from 2 oz. to 48 oz. per square yard. The fabric *A* was a very light cheese cloth, while fabric *H* was a very heavy cotton duck sometimes used for filter cloth. It is apparent from this plot that the rate of increase in the heavy fabric is very much greater than in the light. This is the natural result to be expected when the friction between the fibres is increased by the presence of moisture. If all the fabrics of Fig. 14 be corrected for the moisture present to a common basis of comparison, say 6½ per cent regain, the curves take the form of Fig. 15.

21. Sizing Determination. The natural weight of the fabric is often increased either for legitimate or illegitimate reasons. It is therefore often necessary to determine the weight of the natural fabric, eliminating whatever foreign matter has been added for slashing or weighting.

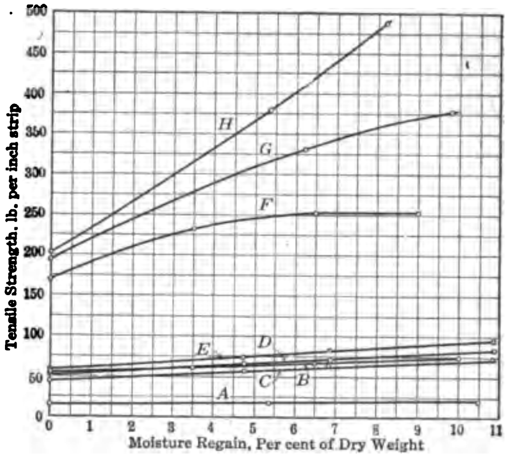


FIG. 14. — Variation in Tensile Strength in Textiles Due to Moisture.

"In order accurately to determine the amount of foreign matter present in fabrics, the Bureau of Standards has recommended the following procedure: Tests for sizing are to be made as follows:

(*a*) Samples approximately 5 gm. in weight are to be dried in tared weighing bottles at 105° to 110° C. (220° to 230° F.) to constant weight.

(*b*) Immerse samples in boiling water for 10 minutes and rinse thoroughly.

(*c*) Digest in solution containing 15 cc. commercial diastofor in 500 cc. water at 60° C. (140 F.) for 2 hours.

(*d*) Wash thoroughly in hot water and then boil for 1 hour in 500 cc. distilled water.

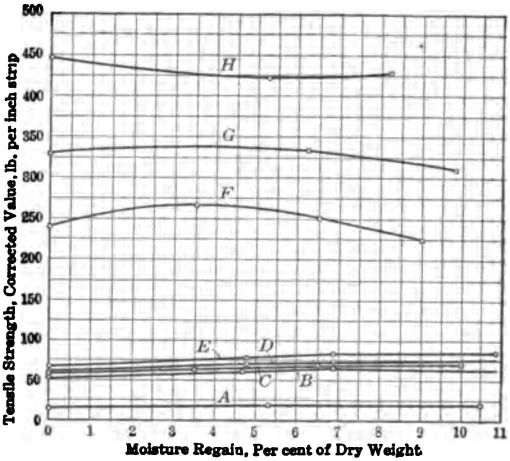


FIG. 15. — Tensile Strength of Fabrics Corrected for Moisture.

(*e*) Dry in tared weighing bottles to constant weight.

(*f*) The loss in weight divided by the original weight of samples will be the percentage of sizing."

22. General Fabric Plots. The effect of moisture on other fibres than cotton is shown by Fig. 16, which shows the results of a series of experiments on ramie, silk both raw and boiled-off and worsteds. It is to be noted that the effect of moisture upon the animal fibres is to decrease the strength of the fabric rather than to increase it.

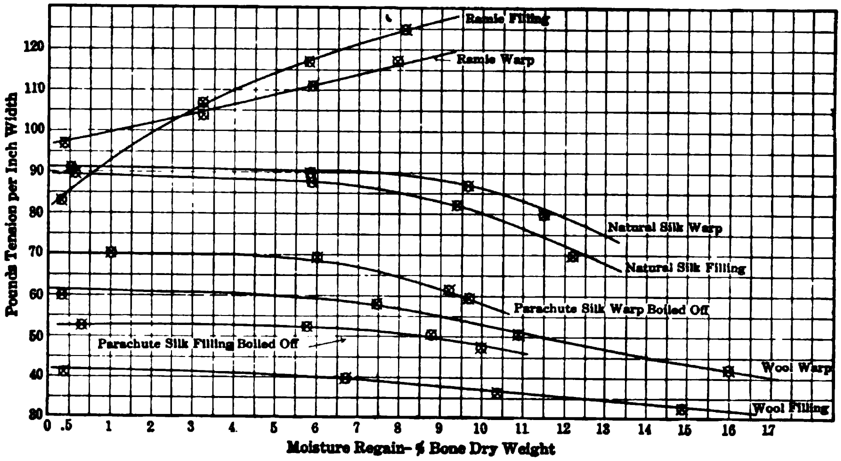


Fig. 16. — Moisture Effect for Various Fabrics

INDEX

Heavy figures indicate sections; light figures pages. The abbreviations A.S.T.M. and I.A.T.M. are American Society for Testing Materials and International Association for Testing Materials, respectively.